Organometallics **2001,** *20,* 2940−2955

Cover Essay

Zinc Alkyls, Edward Frankland, and the Beginnings of Main-Group Organometallic Chemistry

When, on July 28, 1848, Edward Frankland (Figure 1), then a 23-year-old faculty member of Queenwood College in Hampshire, England, filled a thick-walled glass tube with finely granulated zinc and ethyl iodide and then sealed it, he did not realize that he had set up the reaction that would produce the first main-group organometallic compounds, ethylzinc iodide and diethylzinc, our cover molecules (if you accept Zn, Cd, and Hg as honorary main-group elements). His goal was the preparation and isolation of the ethyl "radical". A "radical" in 1848 was the name for a component group of a compound: i.e., a stable group of atoms that retains its integrity in its reactions and in its formation of compounds with other atoms or groups of atoms (generally electronegative). Thus, it was regarded as an organic equivalent of a metal. Organic chemistry in the first half of the 19th century was in a rather disorganized state, and the chemists of the day proposed various "theories" to rationalize and systematize the known types of organic compounds. One such theory was that of "alchohol radicals", i.e., the "R" of ROH, proposed by Liebig and Kane. Berzelius, the great Swedish chemist, was an enthusiastic supporter of the "radical" theory. For instance, he considered acetic acid to be a "conjugate compound" composed of the methyl "radical" (C_2H_3 in those days on the basis of his atomic weight scale in which C = 6 and O = 8) and CO_2H. The cacodyl "radical" of Bunsen, $(CH_3)_4As_2$ (later $(CH_3)_2As$),[1,2] was regarded by the chemists of the day as the first "radical" that actually had been isolated, since it formed "conjugate compounds" with electronegative groups. So the question arose: if the cacodyl "radical" can be isolated in substance, why not organic "radicals" such as methyl, ethyl, phenyl, etc.?

Hermann Kolbe, a young Assistent in Bunsen's laboratory at the University of Marburg, was very interested in this possibility. During a stay in England (1846−1848) as assistant to Lyon Playfair at the Museum of Economic Geology and at Putney College of Civil Engineering, he was engaged in gas analysis, which he had learned in Bunsen's laboratory, but also started some independent research aimed at the isolation of organic "radicals". At about the same time, 21-year-old Frankland joined Playfair's laboratory as a lecture assistant to Playfair. Kolbe and Frankland became good friends, and Kolbe taught Frankland the techniques of gas analysis. Together they undertook an investigation of the basic hydrolysis of aceto-, propio-, and valeronitrile, obtaining in each case, after acidification, the corresponding carboxylic acid.[3] These results agreed with Berzelius' view, since the alkyl groups remained unchanged in the RCN to RCO_2H conversion; therefore, nitriles were regarded as "conjugate compounds" of the alkyl and cyanide radicals.

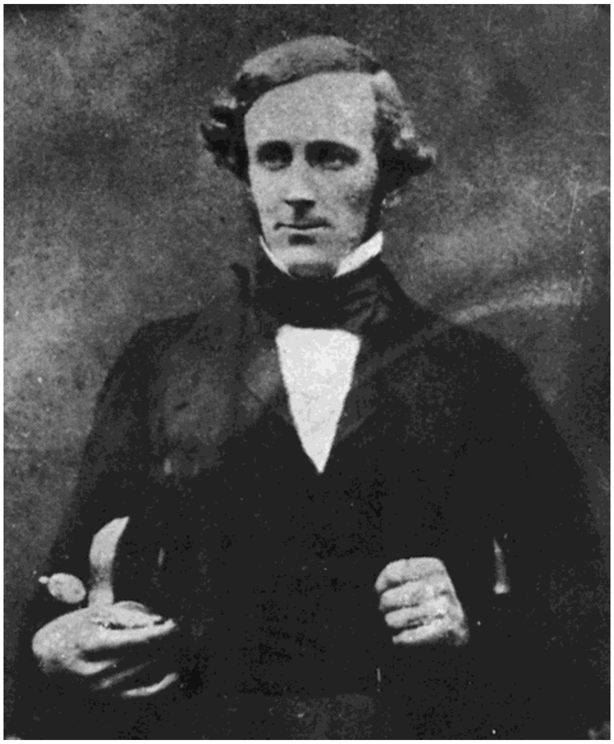

Figure 1. Edward Frankland about 1850 (reproduced courtesy of the Library and Information Centre, Royal Society of Chemistry).

During the summer of 1847, Frankland accompanied Kolbe to Marburg in order to study with Bunsen. His stay in Marburg reinforced his interest in "radicals". In an attempt to prepare the ethyl "radical", Kolbe and Frankland carried out the action of potassium on C_2H_5CN, a rather violent reaction which proceeded with flashes of light and rapid gas evolution.[4] The gas, they thought, was "methyl", not "ethyl", on the basis of its analysis; actually, it was ethane.

On his return to England, Frankland took up a position as science master at the newly founded Queenwood College, and it was here that he carried out his first experiments aimed at the isolation of the ethyl "radical" by the action of a metal on ethyl iodide. His

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[1] See the cover molecule essay that deals in part with Bunsen's research on the cacodyl compounds: Seyferth, D. *Organometallics* **2001**, *20*, 1488.

[2] The electron was unknown in 1848; therefore, the 1848 "radical" has no connection with the free radical of today.

[3] Kolbe, H.; Frankland, E. *Ann.* **1848**, *65*, 288.

[4] (a) Kolbe, H.; Frankland, E. *J. Chem. Soc.* **1849,** *1,* 60. (b) *Ann.* **1848**, *65*, 269.

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first experiment was a sealed-tube reaction of ethyl iodide with potassium. This reaction also was rather violent, and the gaseous products were not the expected "ethyl", but rather again "methyl" (actually a 1:1 mixture of C_2H_6 and C_2H_4, as Frankland realized years later). Thus, perhaps stimulated by the reaction that Bunsen had applied successfully to the isolation of what at that time was considered to be the cacodyl "radical" (eq 1), Frankland set out to investigate the $C_2H_5I + Zn$ reaction and prepared a sealed tube containing these reactants. No reaction occurred until 150 °C, but at ~200 °C the zinc/C_2H_5I reaction proceeded with "tolerable rapidity", giving white crystals and leaving a colorless, mobile liquid. The sealed tube containing this reaction mixture remained sealed for some months because the only eudiometer required for the combustion of the product gases for their analysis was destroyed. In October, Frankland returned to Marburg in order to obtain his Ph.D. under Bunsen's guidance. He took along the sealed tube from his C_2H_5I/Zn experiment at Queenwood College.

$$2(CH_3)_2AsCl + Zn \xrightarrow{\Delta} (CH_3)_4As_2 + ZnCl_2 \qquad (1)$$

Frankland spent the winter of 1848−1849 and spring of 1849 studying the C_2H_5I/Zn reaction, looking for the ethyl "radical". The results of this work were published both in German and in English,[5] and this work served as his Ph.D. dissertation at the University of Marburg. The degree was awarded on June 30, 1849—no 4-year-plus stay and a fat dissertation in those days.

Bunsen's great expertise in gas analysis, which Frankland had mastered while at Marburg, was applied to a study of the gaseous products of the C_2H_5I/Zn reaction. When such sealed tubes were opened with provision for collecting the gaseous products (over water, to remove unconverted ethyl iodide), a large volume of gas was evolved and the mobile liquid disappeared. The collection and analysis of the gases is described in great detail by Frankland, the final result being as follows: elalyl (i.e., ethylene), 21.70%; ethyl, 50.03%; methyl, 25.79%; nitrogen (from adventitious air), 2.48%, all by volume. Frankland firmly believed, then and for some time afterward, that he had produced the ethyl "radical". The isolation of the purported pure ethyl "radical" was facilitated by its high boiling point relative to those of the other gaseous products. It was remarkably inert, being unreactive to fuming sulfuric acid and scarcely affected by concentrated nitric acid: strange properties for a "radical", even by the 1848 definition. Nevertheless, Frankland entitled his paper[5b] "On the Isolation of Organic Radicals". As was realized later, these gases were not the CH_3 and C_2H_5 "radicals" at all, but rather their dimers, the saturated hydrocarbons ethane and *n*-butane.[6]

It was the analysis (by hydrolysis) of the crystalline product of the C_2H_5I/Zn reaction which gave the first indication that an organozinc compound had been formed. Both "methyl" (ethane) and "ethyl" (butane) were produced, but Frankland's experiments indicated that the latter was only "mechanically retained in the interstices of the crystals and eventually evaporated under ordinary atmospheric pressure." The "methyl", however, was not lost under those conditions, and Frankland concluded that "the iodide of zinc combines with a small proportion of "methyl", forming a white, crystalline compound, probably of definite constitution", but he did not make the connection that this crystalline solid contained an organozinc compound, C_2H_5ZnI. He was almost, but not quite, there. Another experiment was carried out in which ethyl iodide, water, and zinc were heated in a sealed tube: a potential bomb, but Frankland's sealed tubes were well-made and survived pressures of 80−100 atm. Only "methyl" (ethane) was formed in this reaction. Frankland did not comment on this result, which must have seemed strange to him: the transformation of the ethyl of ethyl iodide to "methyl". However, he recommended it as the best procedure for the preparation of pure "methyl".

As a final part of this study Frankland investigated, only qualitatively, the action of other metals on ethyl iodide at temperatures between 150 and 200 °C. Iron, lead, copper, and mercury did not appear to have much of an effect, but arsenic and tin did react.

After receiving his Ph.D., Frankland continued his research in Bunsen's laboratory in Marburg. His investigation of the C_2H_5I/Zn reaction had produced some gases and a white, crystalline solid which he did not identify. Without doubt the latter contained ethylzinc iodide and zinc iodide; very likely, the reaction also had produced diethylzinc by thermally induced disproportionation of ethylzinc iodide. However, the diethylzinc, for the most part, probably had decomposed while the sealed tube was heated at 200 °C, giving real ethyl radicals through homolytic Zn−C scission. The ethyl radicals, of course, dimerized (giving *n*-butane) and disproportionated (giving ethane and ethylene). Thus, ethylzinc iodide and diethylzinc were the first alkylzinc compounds that Frankland had prepared, and hence, the first main-group organometallic compounds, although he had not realized it at that time. Nevertheless, we have chosen them as our cover molecules so that they will get the recognition that initially eluded them.

The first organozinc compound that was prepared and identified as such by Frankland was dimethylzinc. Recalling the exciting day of this discovery, Frankland in 1877 provided the following description of his first experiments:[7]

> "Zincmethyl and zincethyl were the first of these [i.e., organometallic] bodies with which I became acquainted: they were discovered on July 12, 1849, in the laboratory of Professor Bunsen in Marburg, during my work on the isolation of the organic radicals. After making the reaction for the isolation

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[5] (a) Frankland, E. *Ann.* **1849**, *71*, 171. (b) *J. Chem. Soc.* **1850**, *2*, 263. Frankland published most of his early work on organometallic chemistry this way: once in German, once in English.

[6] Frankland's empirical formulas for his "radicals" were correct, but the molecular weights that he assigned to them were not. He did not accept Avogadro's hypothesis and so did not know that the molecular weights of the gaseous "radicals" were double the empirical formula weight. Frankland's claimed "methyl" and "ethyl" radicals soon generated controversy. The French chemists Laurent and Gerhardt (*C. R. Trav. Chim.* **1849**, 19; **1850**, 12) maintained that their molecular weights should be doubled, thus making them ethane and butane, homologues of methane, on the basis of Frankland's reported vapor densities. This also would explain their relative inertness. Some chemists supported Gerhardt (e.g., A. W. Hofmann and Würtz); others supported Frankland (e.g., Kolbe). Experiments by Würtz and later by Schorlemmer proved Gerhardt to be right (see: Partington, J. R. *A History of Chemistry*; Macmillan: London, 1964; Vol. 4, pp 508−510).

Table 1

hydrogen series	methyl series	ethyl series	butyl series	valyl series	amyl series	phenyl series
ZnH	ZnC_2H_3*	ZnC_4H_5*	ZnC_6H_7	ZnC_8H_9	$ZnC_{10}H_{11}$	$ZnC_{12}H_5$
AsH_2*	$As(C_2H_3)_2$*	$As(C_4H_5)_2$	$As(C_6H_7)_2$	$As(C_8H_9)_2$	$As(C_{10}H_{11})_2$	$As(C_{12}H_5)_2$
SbH_3*	$Sb(C_2H_3)_3$	$Sb(C_4H_5)_3$	$Sb(C_6H_7)_3$	$Sb(C_8H_9)_3$	$Sb(C_{10}H_{11})_3$	$Sb(C_{12}H_5)_3$
PH_3*	$P(C_2H_3)_3$*	$P(C_4H_5)_3$	$P(C_6H_7)_3$	$P(C_8H_9)_3$	$P(C_{10}H_{11})_3$	$P(C_{12}H_5)_3$

> of methyl by digesting methylic iodide with zinc and after discharging the gases, I cut off the upper part of the tube in order to try the action of water upon the solid residue. On pouring a few drops of water upon the residue, a green-blue flame, several feet long, shot out of the tube, causing great excitement among those present. Professor Bunsen, who had suffered from arsenical poisoning during his research on cacodyl, suggested that the spontaneously inflammable body, which diffused an abominable odor through the laboratory, was that terrible compound, which might have been formed by arsenic present as an impurity in the zinc used in the reaction, and that I might be already irrecoverably poisoned. These forebodings were, however, quelled in a few minutes by an examination of the black stain [which was zinc] left upon porcelain by the flame; nevertheless, I did afterward experience some symptoms of zinc-poisoning."

Frankland recognized the importance of his discovery of methyl- and ethylzinc compounds and immediately realized the potential, more general application of the metal/RI reaction to the preparation of organic derivatives of other metals. He sent a short communication to *Annalen der Chemie und Pharmacie* describing his preliminary results, which was published immediately following his paper on organic radicals.[8a] The same paper was read (in English) at the November 5, 1849 meeting of the Chemical Society in London and published in the *Journal of the Chemical Society* in 1850[8b] under the title "On a new series of Organic Bodies containing Metals and Phosphorus".

In this communication, Frankland mentions that he has been investigating the action of methyl iodide on zinc. He reports on opening the sealed tube, "methyl gas is disengaged and a white, crystalline residue remains in the decomposition tube." Frankland goes on to describe the white solid:

> "The peculiar behavior of this residue with water, which decomposes it, producing brilliant flame, and causing the evolution of pure light carburetted hydrogen [i.e., CH_4] induced me to study it more closely. When the substance was subjected to distillation in an apparatus filled with dry hydrogen, a colorless pellucid liquid, possessing a peculiarly penetrating and exceedingly nauseous odor, condensed in the receiver; this liquid spontaneously inflames on coming in contact with air or with oxygen, burning with a brilliant greenish-blue flame, and forming dense clouds of oxide of zinc, ... The vapour of this compound is highly poisonous, producing shortly after its incautious inhalation, all the symptoms of poisoning by zinc. It decomposes water with as much violence as potassium, the small tube containing a few drops of the liquid becoming red hot under water; the products of this decomposition are oxide of zinc and 2 equiv of pure light carburetted hydrogen, from which it is evident that the body in question is composed of 1 equiv. methyl and 1 equiv. zinc (C_2H_3Zn), for $C_2H_3Zn + HO = ZnO + 2\ (CH_2)$." [Since at that time the atomic weights of C = 6 and O = 8, CH_3 is C_2H_3 and HO is H_2O.]

Frankland's mind was still possessed by the "radical" theory, for he says: "It is highly probable that this body which for the present I propose to call *Zincmethyl*, plays the part of a radical, combining directly with oxygen, chlorine, iodine, &c." Frankland now has an explanation for the observations made in his previous study of the C_2H_5I/Zn reaction, since by a similar procedure he now also had prepared *Zincethyl*, which is somewhat less reactive toward water. Its reaction with water Frankland writes as

$$C_4H_5Zn + HO = ZnO + 2(C_2H_3) \tag{2}$$

In view of these new results with the RI/Zn reactions, Frankland now was able to suggest that the reactions of ethyl iodide with arsenic and tin also give "radicals"—organic derivatives of these elements. He mentions also in this communication that methyl and ethyl iodide react with elemental phosphorus. His communication ends with the prediction that many other organic derivatives of these and other metals will be accessible, writing the table reproduced here as Table 1, with the introduction: "The existence of hydrogen compounds of arsenic, antimony, and tellurium, and the substitution of ethyl and methyl in the new bases of Wurtz, point out the striking similarity between the respective functions of these radicals and of that element, and taken in connection with the above facts, seem to warrant the expectation that most, if not the whole, of the following compounds may be obtained. Those marked with an asterisk are already known."[8b] Frankland knows that he's onto something good and is staking out his claim.

Frankland understood the value of "show and tell": the communication is followed by the comment concerning the meeting in which it was read: "Dr. Hofmann exhibited a specimen of the zincmethyl he had obtained from Dr. Frankland, and demonstrated its spontaneous inflammability."

In the autumn of 1849, Frankland left Marburg for the University of Giessen, where he spent three months working in the laboratory of Justus Liebig, one of the leading chemists of the time. While there he continued his investigations of RI/Zn reactions with *n*-amyl iodide. This iodide was much less reactive toward zinc than

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(7) Frankland, E. *Experimental Researches in Pure, Applied and Physical Chemistry*; John van Voorst: London, 1877. This is an over 1000 page book in which Frankland's published papers up until 1877 are collected, together with his commentary about the topics involved. Those papers originally published in German, for which no English version was published at the time, are presented in English translation, and in all papers modern nomenclature, notation, and formulas based on the correct atomic weights (i.e., C = 12; O = 18) are provided.

(8) Frankland, E. (a) *Ann.* **1849**, *71*, 213. (b) *J. Chem. Soc.* **1850**, *2*, 297.

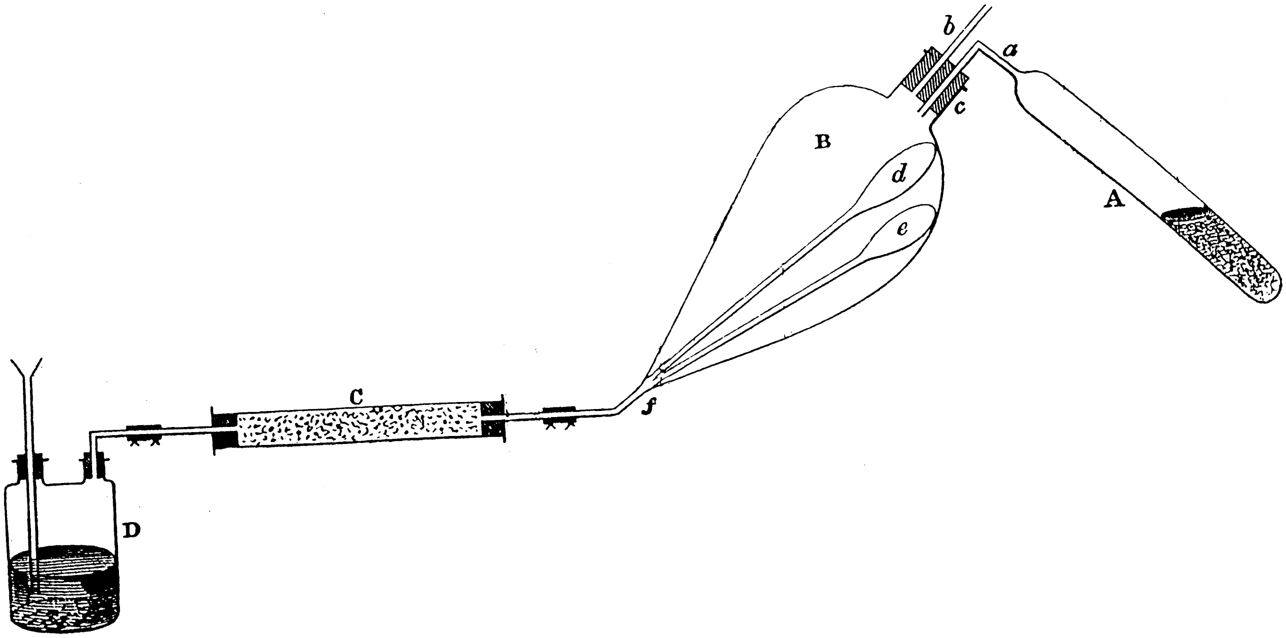

Figure 2. Frankland's apparatus for the distillation of dimethylzinc (from ref 10).

were methyl and ethyl iodide and could not be brought to reaction at higher temperatures because it underwent dehydroiodination instead. These problems were solved by using zinc amalgam rather than zinc: reaction occurred already at the boiling point of amyl iodide. Detailed investigation of the reaction mixture established the formation of "amyl", "amyl hydride", amylene, and "zincamyl", but the last species was not described.[9]

Frankland returned to England when he was offered the Professorship of Chemistry at Putney College as successor to Playfair. His stay there was short; in 1851 he became professor of chemistry at the newly founded Owens College in Manchester. While there, Frankland wrote his full papers on dimethyl-[10] and diethylzinc.[11] These merit closer examination because they illustrate Frankland's experimental ingenuity. Not only was he an accomplished designer and maker of special laboratory glassware (learned from Bunsen in Marburg), but his other metal apparatus types, such as autoclaves, are noteworthy.

The isolation of the volatile, pyrophoric, extremely moisture sensitive, and ill-smelling dimethylzinc in high purity was no trivial task. To achieve this, Frankland designed the apparatus shown in Figure 2 and explained its operation as follows:

> "To obtain this liquid in a state of purity, another tube was charged with iodide of methyl and excess of zinc, and subjected to a heat of 150 or 160 °C until every trace of iodide of methyl was decomposed. The drawn out extremity of the tube being broken off, the included gas was allowed to escape, and the liquid contents were then separated from the solid ones by distillation at a gentle heat, in an atmosphere of dry hydrogen. This was accomplished as shown in the following figure.
>
> **A** is the decomposition tube bent at an obtuse angle at ***a***, and connected with the receiver **B** by the doubly perforated cork ***c***, which also contains the small tube ***b***, open at both ends. The receiver **B** is drawn out at ***f*** until its internal diameter is diminished to about 1/20th of an inch, and this drawn out extremity is connected, by means of a caoutchouc joint, with the chloride of calcium tube **C**, which at its opposite extremity is in connection with a hydrogen gas apparatus **D**. ***d***, ***e*** are two small glass bulbs for preserving the condensed liquid. The apparatus being thus arranged, hydrogen is evolved in **D**, and becoming perfectly dessicated in passing through the chloride of calcium tube **C**, enters the receiver **B** at ***f***, expelling the atmospheric air through the tube ***b***. When the gas has thus streamed through the apparatus for at least a quarter of an hour, and every trace of air has been expelled from **B** and from the bulbs ***d***, ***e*** by diffusion, the extremity of the tube ***b*** is hermetically sealed, at the same moment that the evolution of gas from **D** is interrupted. The drawn out extremity of the receiver **B** being then quickly sealed at ***f***; **B**, ***d*** and ***e*** remain filled with pure dry hydrogen, and **A** with a mixture of gases free from oxygen, as any trace of this element, which might have penetrated there, would be instantaneously absorbed by its contents. **B** is then immersed to its neck in cold water, and a gentle heat cautiously applied to the whole length of **A** by means of a spirit lamp. The mobile fluid in **A** soon enters into ebullition, and distils over into the receiver **B**; as soon as the distillation is finished and **A** become cold, its capillary extremity is fused off at ***a*** by means of a blowpipe, ***a*** remaining hermetically sealed. The receiver **B** is then removed from the water and dried; heat is applied to the side adjacent to the bulbs ***d***, ***e***, so as to expel a portion of the enclosed gas from their open ends at ***f***; on subsequent cooling, a certain quantity of the liquid rises into these bulbs, which are alternately heated and cooled, until every trace of the liquid has not only entered them but passed entirely into their

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[9] Frankland, E. (a) *Ann.* **1850**, *74*, 41. (b) *J. Chem. Soc.* **1851**, *3*, 30.

[10] Frankland, E. (a) *Philos. Trans.* **1852**, *142*, 417. (b) *Ann.* **1853**, *85*, 329.

[11] Frankland, E. (a) *Philos. Trans.* **1855**, *145*, 259. (b) *Ann.* **1855**, *95*, 28.

> expanded portion, so as to leave the capillary limbs filled with hydrogen. It is of importance that the whole of the liquid should be forced to enter these bulbs, otherwise, on subsequently opening the mouth of the receiver, it inflames, causing the expulsion of the liquid from the bulbs, and thus rendering the experiment abortive. The cork ***c*** is then removed, and the bulbs ***d***, ***e*** extracted as quickly as possible, the open capillary extremities being immediately sealed before the blowpipe. The bulbs, having been previously weighed, the increase denotes the weight of the included liquid. The residue in **A** was found scarcely to effervesce with water, and consisted of iodide of zinc mixed with the excess of metallic zinc employed."

Hydrolysis experiments with the distillate (identity of gas evolved through combustion analysis; quantity of gas evolved and weight of ZnO formed) established that the liquid was zincmethyl (dimethylzinc) (C_2H_3Zn, as Frankland wrote it), and he proposed for it the name *Zincmethylium*.

Frankland immediately appreciated the potential utility of dimethylzinc:[10]

> "The extraordinary affinity of zincmethylium for oxygen, its peculiar composition and the facility with which it can be procured cannot fail to cause its employment for a great variety of transformations in organic compounds; by its agency there is every probability that we shall be able to replace oxygen, chlorine &c., atom for atom by methyl, and thus produce entirely new series of organic compounds, and obtain clearer views of the rational constitution of others. I intend to pursue this branch of the subject whilst studying the compounds of zincmethylium and the corresponding bodies containing ethyl and amyl."

Diethylzinc (zincethylium, C_4H_5Zn, as Frankland wrote it) was prepared in a similar manner.[11] It also had a peculiar, penetrating odor but was less reactive toward air, undergoing spontaneous inflammation only when larger quantities were exposed to air. Its instantaneous and vigorous hydrolysis was summarized by eq 3. Di-*n*-amylzinc ("zincamylium", $C_{10}H_{11}Zn$) was even less reactive, fuming in air but not spontaneously inflammable.

$$\left.\begin{matrix} C_4H_5Zn \\ HO \end{matrix}\right\} = \left\{\begin{matrix} C_4H_5H \\ ZnO \end{matrix}\right. \qquad (3)$$

Frankland's sealed-tube syntheses of the dialkylzincs were limited to the preparation of small quantities in low yield. For the preparation of larger quantities, Frankland, with the help of an engineer named Nasmyth, constructed more sturdy metal equipment. Such a "digester" (i.e., autoclave, which can stand the high pressures generated in the C_2H_5I/Zn reaction) is shown in Figure 3. A schematic view of the digester is shown in Figure 3a; the digester is heated in an oil bath contained in a gas stove (Figure 3b). Full details are provided in ref 11. Using such an apparatus, it was possible to prepare 4–5 oz of diethylzinc at one time. A significant improvement in the diethylzinc preparation involved the use of diethyl ether as solvent (1/1 $C_2H_5I/(C_2H_5)_2O$), which almost entirely prevented gas evolution (i.e., decomposition of the diethylzinc which had been formed), resulting in the complete utilization of ethyl iodide and in an almost quantitative yield of diethylzinc. (Frankland, in his first communication,[8] had reported that almost no gas was formed when diethyl ether was present, while Brodie in 1851 reported complete utilization of ethyl iodide in the presence of diethyl ether even at 100 °C[12]). The distillation of diethylzinc was effected in the apparatus shown in Figure 4. Frankland described how it worked.[11]

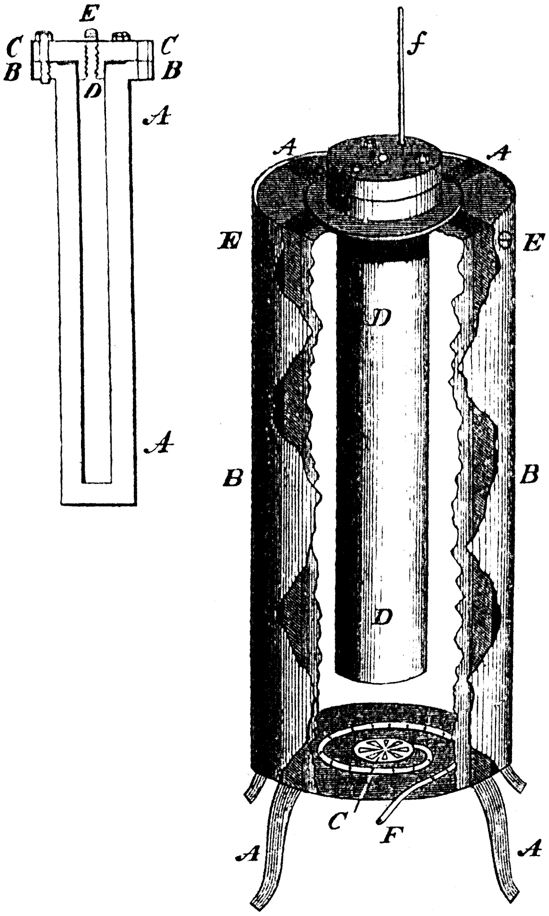

Figure 3. Frankland's "digester": (a, left) schematic view; (b, right) gas stove and oil bath used to heat the digester (from ref 11).

> "As zincethyl is spontaneously inflammable in air and instantaneously decomposed by water, it is necessary that the vessels into which it is distilled should be kept constantly filled, either with dry hydrogen, nitrogen, or carbonic acid gas; the latter I have found most convenient in practice. The maintenance of an atmosphere of this gas can be easily effected by the following arrangement of apparatus, fig. 4. **A** is a Woulf's bottle for the generation of the carbonic acid, which streams through a chloride of calcium tube **B**, and Woulf's bottle **C** containing concentrated sulphuric acid, before entering the reservoir **D**, which should be of about two quarts' capacity, and contain a stratum of concentrated sulphuric acid about one inch deep. From this reservoir the dry gas can be allowed to escape, either by the tube ***e*** into the vessel ***f***, or through the retort ***g*** by the tube ***h***.

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(12) Brodie, B. C. *J. Chem. Soc.* **1851**, *3*, 405.

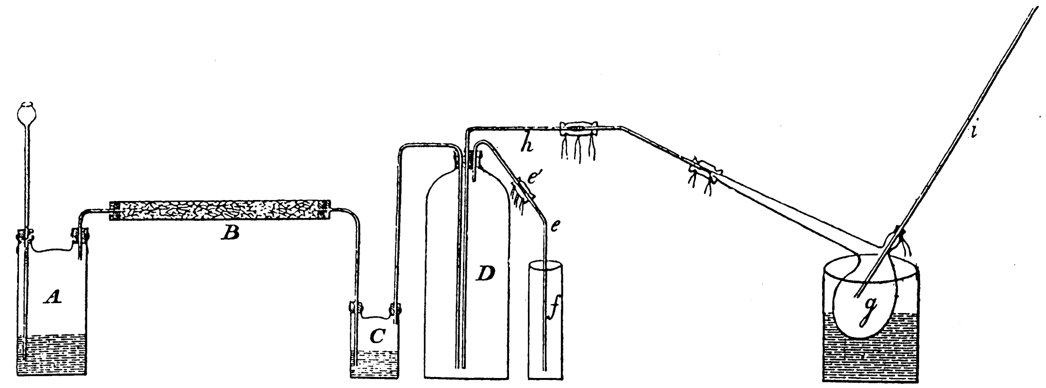

Figure 4. Frankland's apparatus for the large-scale distillation of diethylzinc (from ref 11).

When all is prepared for the distillation of the zincethyl, the reservoir **D** being filled with carbonic acid, and the tube ***i*** from the digester (which latter still remains in the oil-bath and gas-stove) inserted into the tubulure of the retort ***g***, the stream of carbonic acid, which has hitherto flowed through ***f***, is cut off at ***e′*** by a caoutchouc valve, and is thus made to flow through ***g***, making its escape between the tubulure and the tube ***i***. After the carbonic acid has taken this route for a sufficient length of time to ensure the complete expulsion of air from ***g***, a piece of sheet caoutchouc is passed round the tubulure of ***g*** and the tube ***i***, so as to make the union gas-tight, whilst at the same moment an assistant opens the caoutchouc valve ***e′***; thus allowing the carbonic acid again to escape through ***f***. The retort ***g*** is thus connected with a reservoir kept constantly filled with pure and dry carbonic acid, which effectually excludes atmospheric oxygen and moisture from ***g*** during the distillation. Heat being now applied to the digester, by means of the gas-stove and oil-bath, ether begins to distil over, so soon as the temperature of the digester exceeds the boiling-point of that liquid. The first half-ounce is nearly free from zincethyl and might be collected apart, but I generally prefer to receive the whole product of the distillation in one vessel. As the temperature rises to 140° or 150° C. the product becomes more and more rich in zincethyl, but a heat of 190° C. is required to bring over the last portions of this body, a large quantity of which is apparently in some form of combination with the iodide of zinc, and can only be expelled at a very much higher temperature than the boiling-point of zincethyl. During the last stages of the distillation, there is a slow evolution of gas, due to the decomposition of a small portion of the zincethyl by the high temperature required for its complete expulsion.

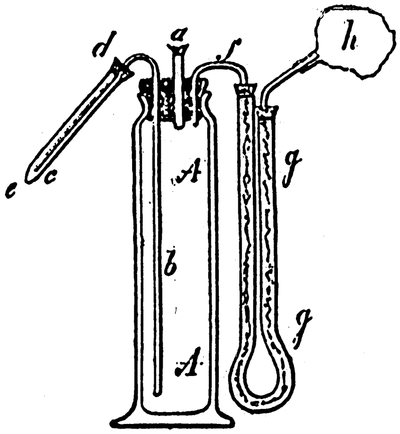

Figure 5. Distillate receiver and storage vessel (from ref 11).

After the whole of the volatile products have passed over, the tube ***i*** must be carefully withdrawn from ***g*** and immediately replaced by a thermometer passing through a well-dried cork. The beak of the retort, disconnected from the tube ***h***, must now be inserted air-tight into a suitable tubulated receiver, previously filled with dry carbonic acid, the tubulure of which is connected with the carbonic acid receiver **D**, and the rectification may now be commenced. The liquid begins to boil at about 60° C., but the thermometer gradually rises until about three-fourths have passed over, when it becomes stationary at 118° C. The receiver must now be changed, the retort being first allowed to become quite cold. On the subsequent application of heat, the whole of the remaining liquid distils over at 118° C. This is pure zincethyl, and may be received in a peculiarly constructed vessel, from which it can be conveniently expelled in small quantities as required.

This vessel, which is a kind of syringe glass, is represented by fig. 5. **A, A** is a tall glass cylinder with a slightly contracted mouth, well fitted with a sound and thoroughly dry cork coated with gutta percha varnish. Through this cork pass three tubes: one ***a***, terminates just below the cork and projects about 2 in. above the mouth of the cylinder; it is about a quarter of an inch internal diameter, and serves to receive the drawn-out beak of the retort ***g*** (fig. 4) during the distillation of the pure zincethyl: when the distillation is completed, ***a*** is closed by a cork covered with sealing-wax. Another tube, ***b***, one-sixteenth of an inch bore, passes to the bottom of **A**; it is bent above at an acute angle, and, after passing through a small cork ***d***, terminates at ***c*** in a capillary orifice. The cork ***d*** serves to close another small tube, ***e***, which encases ***b***, and protects its capillary orifice from the atmosphere. The third tube, ***f***, connects the upper part of **A, A** with a chloride of calcium tube ***g, g***, to the opposite extremity of which the thin caoutchouc globe ***h*** is attached. By removing the tubular cap ***e*** and pressing ***h***, which is previously filled with carbonic acid, it is thus easy to transfer any required quantity of the liquid in **A** to any other vessel."

Distillation of very air-sensitive liquids was more difficult in the 1850s than it is now! A vacuum pump also would have helped. It is clear that Frankland did not realize that the initial crystalline product was ethylzinc iodide. Apparently, he thought at that point that "zincethyl" is in "some form of combination with the iodide of zinc" to give the observed solid.

These procedures are described in such detail to illustrate the painstaking, time-consuming care required in those days when working with extremely air- and moisture-sensitive liquids. Like his teacher Robert Bunsen, Frankland pursued his chemistry with admirable ingenuity, persistence, and fearlessness.

In a curious twist, some 80 years later, Fritz Paneth prepared dimethyl- and diethylzinc by reaction of the gaseous methyl and ethyl radicals (the real things, with an unpaired electron, generated by pyrolysis of tetramethyl- and tetraethyllead, respectively, in the gas phase) with a zinc mirror.[13]

In his 1852 paper[10] Frankland also described his initial results on the preparation of ethyltin compounds. In his initial communication,[8] he had indicated that organoarsenic compounds also were accessible by his RI + M route and suggested that thus "organic bodies that contain metals" (which he later called *organo-metallic compounds*) represent a new and general class of organic compounds.[11] Frankland thought that he would be able to develop this field by himself, but his claim to be the first to prepare such compounds was soon disputed. In 1853, Carl Jacob Löwig, a German chemist at the University of Zürich, published a paper[14] entitled "On the History of Organic Metal Compounds" in which he reported having carried out reactions of an antimony–potassium alloy with ethyl chloride and bromide in 1842 in an effort to obtain antimony analogues of cacodyl. He obtained, he said, a colorless liquid product that fumed strongly in air, which he described in his 1844 organic chemistry textbook[15] and called "Antimonäthyl". He was not able, he said, to continue the investigation of this product until after the publication of Frankland's 1849 paper on the isolation of organic radicals because he was too involved with the writing and publication of his two-volume textbook. However, he did then continue these studies with his co-worker Schweizer and described this work, he said, in November 1849 in the "Communications of the Scientific Society of Zürich".[16] Löwig mentions further publications by himself and his co-workers on the methyl and amylantimony compounds and ethylbismuth in the period 1851–1852, as well as ethyltin and -lead compounds in 1852.[17] Consequently, Löwig took exception to a remark by Frankland in his 1853 paper,[10] which he felt slighted the Löwig/Schweizer paper and did not mention the others at all. Löwig continued on to say that he claimed priority for the discovery and preparation of organometallic compounds by the reactions of ethyl bromide with alloys of potassium or sodium and antimony, bismuth, tin, and lead. He pointed out that, after all, his quest for such organometallic compounds was premeditated, whereas Frankland obtained them only accidentally during his search for the ethyl "radical".

Frankland's reply to this polemic appeared only in 1855.[18] He pointed out that the 1853 paper in *Annalen der Chemie und Pharmacie*[10b] to which Löwig took exception really was written early in 1852 and communicated to the Royal Society in May 1852. It was published in the *Philosophical Transactions* in the same year,[10a] and only in the next year in *Annalen der Chemie und Pharmacie*. Therefore, he was not aware of most of the Löwig papers when he wrote his paper. Furthermore, Löwig was not the discoverer of ethyltin compounds, since both Frankland and Cahours published on them before him. Frankland noted also that Löwig did not mention Frankland's earlier work in his papers, although the first Frankland communication appeared in 1849. The final blow was Frankland's rejection of Löwig's claim to be the first to prepare an organometallic compound. His antimony compound, as described in his textbook, was far from being adequately characterized and, in fact, had been entered as "Antimonäthyl (?)". However, Frankland ended by complimenting Löwig and co-workers on their work, which, he said, has enriched this new field of organometallic chemistry. Löwig, in a rebuttal,[19] strongly disputed what Frankland said and reiterated his claim that his "stibäthyl" was the first organometallic compound, and he also claimed the first organotin compound. He repeated his claim that Frankland's characterization of "zincmethyl" and "zincethyl" in his 1849 communication was insufficient for him to claim them as definite compounds. This publication of Löwig's prompted Frankland to undertake a careful investigation of all dates involved—submission and publication dates of Löwig's papers, dates of when the journals involved reached Zürich and England, and from his diary, dates of Frankland's own experiments.[20] It appeared that some important dates cited by Löwig were not correct and, as a result, Frankland's priority claim to have prepared the first organometallic compound has stood the test of time. Both Frankland and Löwig, now at the University of Breslau, continued their research on organometallic compounds.

Once Frankland had made his breakthrough discovery and published his first papers, the organometallic chemistry of the main-group elements was developed very rapidly: "rapidly" in the relative sense. As shown by the details of Frankland's preparation and isolation of dimethyl- and diethylzinc, the procedures were not as simple as they are today, especially in the case of air-sensitive compounds. The chemists of the 1850s had no inert-atmosphere boxes, Schlenk lines, ground-glass joints, vacuum pumps, etc.; therefore, handling techniques were cumbersome and relatively slow. The protective gases mentioned in their papers were mainly

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(13) (a) Paneth, F.; Hofeditz, W. *Ber. Dtsch. Chem. Ges.* **1929**, *62*, 1335. (b) Paneth, F.; Lautsch, W. *Ber. Dtsch. Chem. Ges.* **1931**, *64*, 2702.

(14) Löwig, C. J. *J. Prakt. Chem.* **1853**, *60*, 348. (Löwig (1803–1890), Privatdozent in Heidelberg, 1830–1833; professor at the University of Zürich, 1833–1853, and at the University of Breslau from 1853. Worked on organometallic compounds, discovered bromoform, other organic research.).

(15) Löwig, C. J. *Chemie der organischen Verbindungen*; Zürich, 1839–1840; 2nd, Braunschweig, 1844–1846; Vol. 2.

(16) Löwig, C.; Schweizer, E. *Ann.* **1850**, *75*, 315. This paper's title is followed by the footnote: "From the Communications of the Scientific Society of Zürich, No. 45, communicated by the authors."

(17) (a) Landolt, H. *Ann.* **1851**, *78*, 91. (b) Breed *Ann.* **1852**, *82*, 106. (c) Landolt, H. *Ann.* **1852**, *84*, 44. (d) Löwig, C. *Ann.* **1852**, *84*, 308.

(18) Frankland, E. *J. Prakt. Chem.* **1855**, *65*, 45.

(19) Löwig, C. *J. Prakt. Chem.* **1855**, *65*, 355.

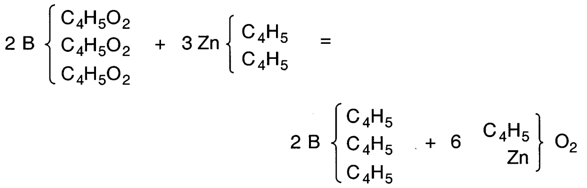
(20) Frankland, E. *Ann.* **1856**, *95*, 333.

carbon dioxide, hydrogen, and coal gas. The first two had to be generated and dried during the course of the experiment. The choice of solvents was limited. Also, one need only read the publications of those days to appreciate how much time and effort the analytical procedures required. Nevertheless, the period 1850−1875 saw the preparation of the organometallic compounds of many of the other main-group metals and the development of their chemistry, including their application in organic synthesis (especially of the dialkylzincs). Frankland was a main participant in these developments, and he quickly had company; chemists from Germany, France, England, and Russia were attracted into this new area on the borderline of organic and inorganic chemistry. Those years were very much like the ones after the discovery of ferrocene, except that there were fewer chemists involved and, as noted above, the pace was a bit slower.

Frankland, while continuing to work on dialkylzinc compounds, followed up on the early leads mentioned in his 1849 communication and investigated the synthesis of organic derivatives of other metals. The reaction of ethyl iodide with an excess of tin foil was induced either by heating to 180 °C or, preferably, photochemically by placing the sealed tube containing the reactants near the focus of a large platinized parabolic reflector (when the sun was shining) with appropriate means of cooling.[10] The major product was $(C_2H_5)_2SnI_2$. Further extensions of this organotin chemistry saw the application of his new dialkylzincs as alkylating reagents, a role in which they were to play an important part in the development of organometallic chemistry up to the present time. The reactions of diethyltin diiodide with diethyl- and dimethylzinc gave $(C_2H_5)_4Sn$ and $(C_2H_5)_2(CH_3)_2Sn$, respectively.[21] Tetraethyltin also was prepared by the reaction of diethylzinc with stannous chloride, the initially formed $[(C_2H_5)_2Sn]_n$ undergoing disproportionation to metallic tin and $(C_2H_5)_4Sn$.[22] Organomercury compounds also were prepared: methylmercuric iodide (or "iodide of hydrargyromethylium", as Frankland called it) by the sunlight-induced reaction of methyl iodide with metallic mercury[10] and R_2Hg ($R = CH_3$, C_2H_5, n-C_5H_{11}) by reaction of sodium amalgam with the alkyl iodide in the presence of ethyl acetate.[23,24] The reactions of these dialkylmercurials with metallic zinc provided another route to dialkylzincs[24,25] (eq 4).

$$R_2Hg + Zn\ (\text{excess}) \xrightarrow{\Delta} R_2Zn + Zn/Hg \qquad (4)$$

Frankland and Duppa prepared the first organoboron compound, triethylborane, using diethylzinc to alkylate triethyl borate,[26] as written in eq 5 (old atomic weights). With this new compound, Frankland had another product that was pyrophoric: it inflamed in air, burning with a beautiful green flame, and exploded with pure oxygen. They studied its controlled oxidation, obtaining EtB(OEt)$_2$ and hydrolyzing the latter to EtB(OH)$_2$ and ethyl alcohol. Even more reactive toward air was the gaseous trimethylborane, prepared using dimethylzinc, burning with, as Frankland says, "a splendid green flame" on exposure to air.



$$2\,B\left\{\begin{matrix}C_4H_5O_2\\C_4H_5O_2\\C_4H_5O_2\end{matrix}\right. + 3\,Zn\left\{\begin{matrix}C_4H_5\\C_4H_5\end{matrix}\right. = 2\,B\left\{\begin{matrix}C_4H_5\\C_4H_5\\C_4H_5\end{matrix}\right. + 6\left.\begin{matrix}C_4H_5\\Zn\end{matrix}\right\}O_2 \qquad (5)$$

As noted above, while Frankland was busy working to develop organometallic chemistry, so were others. His main competitors were Löwig, first at the University of Zürich, then at the University of Breslau in Germany, and Auguste Cahours of the École Polytechnique in Paris. Löwig has already been mentioned. During the period 1850−1861, he and his students[27] (Schweizer, Landolt, Dünnhaupt, Berlé, Merck, Raimund Löwig (his son), Friedländer, Grimm, Breed (an American from New York), Scheibler) prepared, by reaction of the respective sodium−pnictogen alloy with an alkyl iodide, $(C_2H_5)_3As$, $(CH_3)_3Sb$, $(C_2H_5)_3Sb$, $(n\text{-}C_5H_{11})_3Sb$, and $(C_2H_5)_3Bi$ and studied their chemistry, including the cleavage of the last species with mercuric halides to form ethylmercuric halides. Also prepared during this period were ethyl- and n-amyltin compounds as well as tetramethyllead.

In France, Cahours and Riche reported the synthesis of methyl- and ethyltin iodides by reaction of metallic tin with the respective organic iodide in 1852−1853. Cahours' research in organometallic chemistry continued on into the 1870s, dealing with methyl, ethyl, and n-propyl compounds of arsenic, mercury, tin, and lead. The reaction of ethyl and methyl iodide with aluminum gave the respective highly reactive, inflammable methyl- and ethylaluminum iodides. The action of diethylzinc on the latter resulted in formation of (presumably) triethylaluminum, a highly inflammable liquid which Cahours did not further characterize. Also prepared, but not characterized, was a solid product, presumably ethylberyllium iodide, by the reaction of ethyl iodide with metallic beryllium. Dry distillation of this product gave a water-sensitive liquid. (In those days, beryllium was called glucinium because its salts had a sweet taste.) This quick-and-dirty approach was very different from that of Bunsen, Frankland, and Löwig, and it remained for later workers to properly characterize these compounds.

Also broadly active early in the development of organometallic chemistry was another Englishman, George B. Buckton, a versatile chemist who tried out all known methods in his syntheses. He prepared $(CH_3)_2Hg$ by thermolysis of CH_3HgCN, $(C_2H_5)_2Hg$ by reaction of diethylzinc with C_2H_5HgI, $(C_2H_5)_4Sn$ by reaction of diethylzinc with $(C_2H_5)_2SnI_2$ or $SnCl_4$, $(CH_3)_3Al$ and $(C_2H_5)_3Al$ by reaction of metallic aluminum with the respective dialkylmercurial, tetraethyl-

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[21] (a) Frankland, E. *Philos. Trans.* **1859**, *149*, 401. (b) *Justus Liebigs Ann. Chem.* **1859**, *111*, 45.

[22] Frankland, E. *J. Chem. Soc.* **1879**, *35*, 130.

[23] Frankland, E. *J. Chem. Soc.* **1863**, *16*, 415.

[24] Frankland, E.; Duppa, B. F. *Ann.* **1864**, *130*, 104.

[25] Frankland, E.; Duppa, B. F. *J. Chem. Soc.* **1864**, *17*, 29.

[26] (a) Frankland, E.; Duppa, B. F. *Ann.* **1860**, *115*, 319. (b) Frankland, E.; Duppa, B. F. *Proc. R. Soc. London* **1860**, *10*, 559. (c) Frankland, E. *Philos. Trans.* **1862**, *152*, 167. (d) Frankland, E. *Ann.* **1862**, *124*, 129. (e) Frankland, E. *Proc. R. Soc. London* **1877**, *25*, 165.

[27] In those days, it seemed usual for the doctoral students to publish their work alone without their professor, with an appropriate expression of thanks to the professor at the end of the paper, a practice that would make impossible the academic publication lists of 500+ papers of today.

lead by reaction of diethylzinc with $PbCl_2$ (eq 6), and,

$$(C_2H_5)_2Zn + PbCl_2 \rightarrow [(C_2H_5)_2Pb]_n \rightarrow (C_2H_5)_4Pb + Pb \quad (6)$$

very likely, $(CH_3)_5Sb$ by reaction of $[(C_2H_5)_4Sb]I$ with diethylzinc, although it was not isolated in the pure state. The aluminum alkyls, however, were properly characterized, and Buckton is credited with their first preparation.

In addition to the main players, Frankland, Löwig, Cahours, and Buckton, other chemists on the Continent and in England contributed to the growth and development of main-group organometallic chemistry in the 1850−1875 period.[28] However, we are concerned here with the alkylzinc compounds and their discoverer, Edward Frankland.

The development of main-group organometallic chemistry, with the discovery of the peralkyl derivatives of many of the main-group metals, had a crucially important consequence for the development of chemistry as a whole: it led Frankland to the concept of valency.

His own words[7] tell how this realization came to him.

> "I had not proceeded far in the investigation of those [i.e., organometallic] compounds, before the facts brought to light began to impress upon me the existence of a fixity in the maximum combining value or capacity of saturation in the metallic elements which had not before been suspected. That stannous ethide refused to combine with more than the complementary number of atoms of chlorine &c. necessary to form a molecule asymmetrical with stannic chloride surprised me greatly at first; but such behavior in this and other organometallic bodies scarcely permitted of misinterpretation. It was evident that the atoms of zinc, tin, arsenic, antimony, &c. had only room, so to speak, for the attachment of a fixed and definite number of the atoms of other elements, or, as I should now express it, of the bonds to other elements. This hypothesis, which was communicated to the Royal Society on May 10, 1852, constituted the basis of what has since been called the doctrine of atomicity or equivalence of elements; and it was so far as I am aware, the first announcement of that doctrine."

In 1852, when Frankland wrote the paper[10] that contained this seminal idea, he was only 27 years old. His concept was an important advance in the theory of chemical compounds which had become bogged down in disputes between the champions of the "radical theory" and the "type theory". There was much discussion, pro and con, of Frankland's "doctrine of atomicity" throughout the European chemical community, and it prevailed. Its development was quite complicated, with many cooks stirring the pot, suggesting different notations and nomenclature. Valency bonds, as we use them today, came into use, although they indicated only connectivity. For a short discussion of valency, the reader is referred to Partington,[29] but two books have been devoted to this subject.[30]

Figure 6. Edward Frankland (reproduced courtesy of the Library and Information Centre, Royal Society of Chemistry).

Before we continue with a discussion of the further developments of the alkylzinc compounds, it might be appropriate to tell a bit about Edward Frankland, for he was one of the leading English chemists of the second half of the 19th century[31,32] (Figure 6).

Edward Frankland was born on January 18, 1825, in Lancashire, England, the illegitimate son of a distinguished lawyer. Apprenticed to a Lancaster druggist at the age of 15, he learned little from the druggist, but two local doctors gave him his first contact with things chemical, giving him the facilities to carry out some chemical experimentation in his spare time. When he was 20, they arranged his employment in London as Lyon Playfair's lecture assistant in the government's Museum of Economic Geology. It was there he met Hermann Kolbe, who had a significant influence on his development as a chemist, teaching him Bunsen's methods of gas analysis and getting him interested in the "radical theory". Frankland became Playfair's as-

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(28) Useful references are found in: (a) Krause, E.; von Grosse, A. *Die Chemie der metallorganischen Verbindungen*; Gebrüder Borntrāger: Berlin, 1937 and 1943. (b) Partington, J. R. *A History of Chemistry*; Macmillan: London, 1964; Vol. 4, pp 510−511.

(29) Partington, J. R. *A History of Chemistry*; Macmillan: London, 1964; Vol. 4, pp 511−515.

(30) (a) Palmer, W. G. *A History of the Concept of Valency to 1930*; Cambridge University Press: Cambridge, U.K., 1965. (b) Russell, C. A. *The History of Valency*; Leicester University Press: Leicester, U.K., 1971.

(31) For an excellent biography of Frankland, see: Russell, C. A. *Edward Frankland. Chemistry, Controversy and Conspiracy in Victorian England*; Cambridge University Press: Cambridge, U.K., 1996.

(32) Some shorter biographical sketches are listed in the references that follow: (a) Brock, W. H. In *Dictionary of Scientific Biography*; Gillispie, C. C., Ed.; Charles Scribner Sons: New York, 1976; Vol. 5, pp 124−127. (b) Wislicenus, J. *Ber. Bunsen-Ges. Phys. Chem.* **1900**, *33*, 3847. (c) Tilden, W. *Famous Chemists*; George Routledge & Sons: London, 1921; pp 215−227. (d) Partington, J. R. *A History of Chemistry*; Macmillan: London, 1964; Vol. 4, Chapter 16 (which also deals with Kolbe).

sistant at the Civil Engineering College at Putney in London in 1846, and it was at these two schools that Kolbe and Frankland carried out the collaborative work mentioned earlier. After spending the summer of 1847 in Marburg, Frankland returned to England to become science master, together with John Tyndall, at Queenwood College in Hampshire. After his stay in Marburg and, briefly, Giessen in 1848−1849, Frankland was appointed to Playfair's chair of chemistry at Putney, a position he held until 1851, when he became professor of chemistry at Owens College in Manchester. In 1857, he returned to London, where until 1864 he was lecturer in chemistry at St. Bartholomew's Hospital. During this time (1859−1863), he also was a lecturer in science at Addiscombe Military College, and from 1863 to 1869 he held an appointment, as successor to Faraday, as professor of chemistry at the Royal Institution. In 1865, he succeeded A. W. Hofmann (who returned to Germany) as professor of chemistry at the Royal College of Chemistry (which became Imperial College). This appointment he held until his retirement in 1885. Frankland served as president of the Chemical Society (1871−1873) and was the founding president of the Institute of Chemistry in 1877.

After 1865, Frankland published little further research on organometallic chemistry except for papers on tetraethyltin and -lead in 1879 and a group of papers in 1880 on the reactions of diethylzinc with various organic compounds. In 1865, Frankland started making official monthly analyses of London's water supply; from 1868 to 1874, he served on the Royal Commission on River Pollution. He became very interested in the analysis of water, developing new methods for determination of carbon and nitrogen in water. For his important work as a member of the Royal Commission and on water analysis and purification, Frankland was knighted in 1897.

As was the case with many chemists of the 19th century, Frankland's interests and activities ranged very broadly—into physics, astronomy, and botany. A selection of some titles of his papers illustrates this:

"Rapidity of Combustion of Candles on Mont Blanc" (1859)

"On the Composition of Air on Mont Blanc" (1860)

"On the Blue Band of the Lithium Spectrum" (1861)

"On the Influence of Atmospheric Pressure Upon the Burning of Time Fuses" (1861)

"On the Igniting Point of Coal Gas" (1862)

"On Magnesium as a Source of Light" (1865)

"On the Physical Causes of the Glacial Epoch" (1864)

"On the Origin of Muscular Power" (1866)

"On the Analysis of Potable Water" (1868)

"Researches on Gaseous Spectra in Relation to the Physical Constitution of the Sun, Stars and Nebulae" (1869)

This title merits a comment. In 1868, Frankland and Norman Lockyer, an amateur astronomer, during an eclipse of the sun, carried out spectral analysis of one of the solar prominences. The spectrum contained a bright line for which there was no counterpart in the spectrum of any known element on earth. Concluding that it was due to an element found only on the sun, they called it "helium".[33]

A few more titles:

"Purification of Liquid Waste from Manufacturies" (1870)

"On Colored Solar Halos" (1876)

"Transport of Solid and Liquid Particles in Sewer Gases" (1877)

"Chemistry of Storage Batteries" (1883)

The variety is impressive!

Frankland also was very interested and active in chemical education. His textbook *Lecture Notes for Chemical Students* (1866) was influential in its time.

Frankland liked to travel and enjoyed the outdoors; he loved Norway especially and died there while on vacation in 1899, the same year that his great teacher, Robert Bunsen, died.

Let us return to organozinc chemistry. A notable advance in the preparation of the dialkylzincs over the original "no solvent" procedure was the use of ethereal solvents. The preparation of diethylzinc by the C_2H_5I/Zn reaction when carried out in diethyl ether worked well; see for instance ref 34. The CH_3I/Zn reaction also went very well when carried out in diethyl ether solution at 100 °C in Frankland's digestor.[21] Methyl iodide consumption was complete, only very little gas was formed, and a high yield of dimethylzinc was obtained. However, dimethylzinc (bp 44 °C) and diethyl ether (bp 35 °C) could not be separated by distillation and the distillate was a 2:1 mixture of dimethylzinc and diethyl ether. Use of only 3−4% diethyl ether as an additive in the CH_3I/Zn reaction did not result in complete reaction. Replacement of diethyl ether by dimethyl ether (bp −21 °C) as solvent was tried, but, although the reaction proceeded well, the distillate was a 2:1 mixture of $(CH_3)_2Zn$ and $(CH_3)_2O$. Frankland devoted several pounds of methyl iodide to these experiments but never was able to obtain pure dimethylzinc when either dimethyl or diethyl ether was used as solvent or additive. J. A. Wanklyn[35] was able to improve on this by carrying out the CH_3I/Zn reaction using a highly concentrated solution of $(CH_3)_2Zn$ in diethyl ether as the solvent, obtaining pure dimethylzinc in this way.

An important improvement in the direct RI/Zn reaction was made by Gladstone and Tribe in 1873,[36] who discovered that the zinc metal could be activated by adding copper. This resulted in faster rates and in high yields. Over the years, other workers published recipes for what they claimed were more effective, more easily prepared zinc−copper couples. Thus, A. Lachman in the United States described an improved zinc−copper couple for the preparation of diethylzinc[37] in a two-stage process. First, equal weights of ethyl iodide and Zn/Cu couple were heated gently on a water bath until the ethyl iodide was consumed; then the ethylzinc iodide thus prepared was heated at 180−220 °C under dry

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[33] Apparently, Frankland had second thoughts about this, according to a letter that he wrote to Lockyer in 1872: footnote 5 in ref 32a.

[34] Pebal, L. *Ann.* **1861**, *42*, 22.

[35] Wanklyn, J. A. *J. Chem. Soc.* **1861**, *13*, 124 (Wanklyn (1834−1906), assistant to Frankland at Owen's College in 1856; with Bunsen, 1857−1859; assistant to Playfair in Edinburgh, 1859−1865; professor in the London Institution; public analyst.).

[36] (a) Gladstone, J. H.; Tribe, A. *J. Chem. Soc.* **1873**, *26*, 445, 678, 961. (b) *J. Chem. Soc.* **1879**, *35*, 567.

[37] Lachman, A. *Am. Chem. J.* **1897**, *19*, 410; **1900**, *24*, 31. (A very detailed description of the two-step preparation of diethylzinc; its distillation, handling, analysis and storage—all with a CO_2 protective atmosphere and good cork stoppers.).

CO_2. Disproportionation to $(C_2H_5)_2Zn$ and ZnI_2 occurred. The reaction of methyl iodide with zinc is about 100 times less rapid than that of ethyl iodide;[36] therefore, preparation of an active Zn/Cu couple is more important in the case of the CH_3I/Zn reaction. This point was addressed by Renshaw and Greenlaw,[38] whose Zn/Cu couple was very effective in the preparation of $(CH_3)_2Zn$. These workers also discovered the activating effect of acetonitrile and ethyl acetate on the RI−Zn/Cu reaction. An *Organic Syntheses* preparation of dimethyl- and diethylzinc used a zinc/copper alloy containing 10% copper. Another recipe for zinc/copper and zinc/silver couples by LeGoff has been used to good advantage; it also works with CH_2Br_2.[40] In the preparation of dimethylzinc, use of a high-boiling ether such as di-*n*-butyl ether or polyglycol ethers such as diglyme (which were not available—or even known—in Frankland's time) allow the easy isolation of the low-boiling product.

Zinc powder had already been used by early workers. In recent years, very finely divided, high-surface-area zinc has been found to be especially reactive toward alkyl halides: not only toward iodides but also toward bromides. Several different procedures for the preparation of the very high surface area, very reactive zinc powders or dispersions have been described. The "metal atom" approach in which zinc vapor generated under high vacuum by suitable energy input is condensed at 77 K in an ethereal solvent works very well.[41] Even alkyl bromides react at room temperature with such zinc slurries.

The reduction of a zinc halide with an alkali metal in ethereal or hydrocarbon medium under argon has been used by Rieke and co-workers to prepare highly reactive zinc slurries.[42] The most active zinc resulted when anhydrous zinc chloride was reduced with potassium in THF: such samples reacted with iodo- and even bromobenzene (which did not react with any Zn/Cu couples).

Other workers[43] found that ultrasound accelerated the $Li/ZnCl_2$ reaction, giving a zinc powder equally as reactive as that prepared by the potassium/$ZnCl_2$ procedure. According to a 1939 du Pont patent,[44] a better alkali-metal reducing system is obtained when a polynuclear aromatic hydrocarbon such as naphthalene, anthracene, or biphenyl is added in stoichiometric or substoichiometric amounts, using a solvent that can effectively solvate the alkali-metal cation. In this procedure, electron transfer from the alkali-metal atom to the lowest unoccupied antibonding π molecular orbital of the aromatic hydrocarbon forms a radical anion of the latter and a solvated alkali-metal cation. Polyethers such as the glycol ethers and also THF (but not diethyl ether) were found to be effective solvents, and sodium served well as the alkali metal. Such radical anion salts are strong reducing agents and were applied to good advantage to the generation of many highly active metal powders, including magnesium and zinc. This procedure was rediscovered in 1955 by Chu and Friel,[45a] who used it to reduce $CoCl_2$ to metallic cobalt and rediscovered once again by Rieke et al. in 1981,[45b] who have used it to prepare what they call "Rieke metal powders" including highly reactive zinc powders. These have been used to prepare diverse organozinc halides.

The direct RI/Zn reaction is not the only route to dimethyl- and diethylzinc. The Grignard reagents CH_3MgX and C_2H_5MgX (X = Br, I), discovered in 1900, react readily with zinc halides and provide a useful route to these zinc alkyls. However, the presently recommended procedures for the preparation of dimethyl- and diethylzinc use the commercially available trimethyl- and triethylaluminum as alkylating reagents. The synthesis of dimethylzinc is carried out in the apparatus shown in Figure 7.[46] (How happy Frankland would have been to have had such off-the-shelf glassware with its ground-glass joints and Teflon sleeves and stopcocks, as well as tank nitrogen as the inert gas!) Anhydrous zinc acetate and decalin are charged into the reaction flask and cooled to −10 °C, and the trimethylaluminum is added slowly. After about 2 h at 10 °C, the reaction mixture is heated to 115−120 °C, at which point the dimethylzinc distills into the receiver: this is a much simpler synthesis than Frankland's. Diethylzinc is prepared in a similar manner by reaction of triethylaluminum with anhydrous zinc chloride.[47] No solvent is used. In each of these syntheses, only one of the three alkyl groups of the trialkylaluminum reagent is utilized.

Dimethyl- and diethylzinc now are prepared commercially on a large scale by the organoaluminum route and are available from Akzo-Nobel Polymer Chemicals in Deer Park, TX.[48,49] A variation of the R_3Al/ZnX_2 reaction has been developed in which an ethylzinc halide is generated in situ by reaction of an ethyl chloride−ethyl iodide mixture with electrolytic zinc in the presence of the aluminum alkyl.[50]

Now that we have dealt with the synthesis of diethylzinc, one of our cover molecules, it is of interest to consider some of its properties and a few of its basic chemical reactions. Jander and Fischer,[51] in an examination of diethylzinc as a solvent in inorganic and organometallic chemistry, very carefully studied its physical properties, considering available literature values, correcting them if needed and filling in some blanks: density, melting point, boiling point at 760 mmHg, refractive index, viscosity, and specific conductivity. Its explosive reaction with bulk water has already been mentioned. Its oxidation has been the subject of several studies. Frankland had already noted that its controlled oxidation gives $Zn(OEt)_2$. Demuth and Meyer[52] claimed that the white powder produced by its

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(44) Scott, N. D.; Walker, J. F. U.S. Patent 2,177,412 (to E. I. du Pont de Nemours and Co.), Oct. 24, 1939.

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(49) Akzo Nobel Product Data Sheets, "Dimethylzinc", "Diethylzinc", "Dimethylzinc Select Semiconductor Grade", "Diethylzinc Select Semiconductor Grade", 2001.

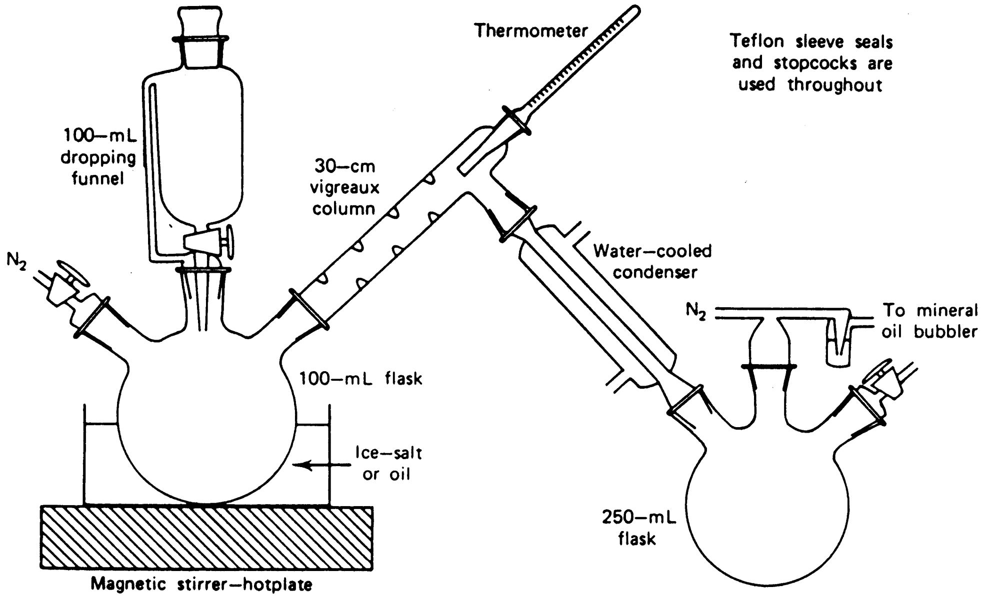

Figure 7. Apparatus of Galyer and Wilkinson for the preparation and distillation of dimethylzinc (from ref 46 by permission of the editor, Marcetta Darensbourg).

oxidation in ligroine is a peroxide, $C_2H_5ZnOOC_2H_5$. This material decomposed explosively when a large quantity was heated quickly under vacuum. However, this formulation is questionable, since acid hydrolysis of the powder gave only ethanol and no ethane. A study of the autoxidation of diethylzinc by Davies and Roberts[53] established that a free radical (S_H2) chain process occurred in anisole solution:

$$R^\bullet + O_2 \rightarrow ROO^\bullet$$

$$ROO^\bullet + (C_2H_5)_2Zn \rightarrow ROOZnC_2H_5 + C_2H_5{}^\bullet$$

$$C_2H_5{}^\bullet + O_2 \rightarrow C_2H_5OO^\bullet \quad \text{etc.}$$

The oxidation product was $C_2H_5OZnOOC_2H_5$, which would explain why Demuth and Meyer found no ethane. The $-ZnOC_2H_5$ grouping is derived from the process

$$-ZnC_2H_5 + C_2H_5OOZn- \rightarrow 2C_2H_5OZn-$$

In the gas phase, diethylzinc reacted with oxygen to give $C_2H_5ZnOC_2H_5$ or $Zn(OC_2H_5)_2$, depending on the stoichiometry used.[54] Diethylzinc is thermally stable to around 200 °C; at temperatures above 200 °C, it undergoes homolytic Zn−C cleavage. The resulting ethyl radicals dimerize to *n*-butane and disproportionate, giving equimolar amounts of ethane and ethylene, as Frankland eventually found out. The heat of formation of diethylzinc (defined by $Zn(s) + 4C(graphite) + 5H_2(g) = (C_2H_5)_2Zn(l)$) is endothermic: $+4.1$ kcal/mol[55a] or $+4.3 \pm 1.0$ kcal/mol.[55b] Diethylzinc in the solid state has a linear structure with $d(Zn{-}C) = 1.93$ Å.[56]

Dimethyl- and diethylzinc were the first available sources of nucleophilic alkyl groups, useful for the alkylation of inorganic and organometallic halides and of organic C═O and C≡N-containing electrophiles. Early examples of the alkylation of metal−halogen functions by Frankland and others have been mentioned above, and the dialkylzincs have been useful in this application ever since. Since they are less reactive than the comparable Grignard and organolithium reagents, they are particularly useful in the partial alkylation of element polyhalides, e.g., $PCl_3 \rightarrow RPCl_2$.

The first use of a dialkylzinc in organic synthesis appears to have been reported by Freund of the University of Lemberg in 1861.[57] On the search for a synthesis of ketones, he added acetyl chloride to diethylzinc. He had a difficult time obtaining a pure product but finally identified it as $CH_3C(O)C_2H_5$:

$$2CH_3C(O)Cl + (C_2H_5)_2Zn \rightarrow 2CH_3C(O)C_2H_5 + ZnCl_2 \quad (7)$$

Later workers found alkylzinc halides to be equally effective in the synthesis of ketones (vide infra). Freund also prepared $(C_2H_5)_2CO$ by reaction of diethylzinc with propionyl chloride and acetone by reaction of dimethylzinc with acetyl chloride.

Frankland was not far behind. In 1863, he reported the monoethylation of diethyl oxalate with diethylzinc,[58] writing the equations

$$\mathrm{C_2}\left\{\begin{array}{l}\mathrm{O}\\ \mathrm{O}\\ \mathrm{C_2H_5O}\\ \mathrm{C_2H_5O}\end{array}\right. + \mathrm{Zn_2}\left\{\begin{array}{l}\mathrm{C_2H_5}\\ \mathrm{C_2H_5}\end{array}\right. = \mathrm{C_2}\left\{\begin{array}{l}\mathrm{C_2H_5}\\ \mathrm{C_2H_5}\\ \mathrm{O}\\ \mathrm{ZnO}\\ \mathrm{C_2H_5O}\end{array}\right. + \left.\begin{array}{c}\mathrm{Zn}\\ \mathrm{C_2H_5}\end{array}\right\}\mathrm{O}$$

$$\mathrm{C_2}\left\{\begin{array}{l}\mathrm{C_2H_5}\\ \mathrm{C_2H_5}\\ \mathrm{O}\\ \mathrm{ZnO}\\ \mathrm{C_2H_5O}\end{array}\right. + \left.\begin{array}{c}\mathrm{H}\\ \mathrm{H}\end{array}\right\}\mathrm{O} = \mathrm{C_2}\left\{\begin{array}{l}\mathrm{C_2H_5}\\ \mathrm{C_2H_5}\\ \mathrm{O}\\ \mathrm{HO}\\ \mathrm{C_2H_5O}\end{array}\right. + \left.\begin{array}{c}\mathrm{Zn}\\ \mathrm{H}\end{array}\right\}\mathrm{O}$$

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In a similar reaction, Saytzeff and Wagner converted ethyl formate to the secondary alcohol $(C_2H_5)_2CHOH$ using diethylzinc.[59] Butlerow, in Russia, prepared *tert*-butyl alcohol by reaction of 2 equiv of dimethylzinc with acetyl chloride on a large scale, using 250 g of dimethylzinc.[60] In this paper, Butlerow disputes Frankland's report of the toxic effects of dimethylzinc, saying that he and co-workers had worked with this compound for 5 years without taking any special precautions and never had a problem. He noted that smoking in the presence of dimethylzinc vapors (or, more correctly, vapors of the oxidation and hydrolysis products of dimethylzinc) changes the taste of the tobacco; it becomes unpleasantly sweetish. (No OSHA in those days.) In a series of short papers in 1880, Frankland returned to diethylzinc, reporting its reactions with a number of nitriles: PhCN,[61] $PhCH_2CN$,[62] PhC(O)CN,[63] and cyanogen, NC−CN,[64] as well as with azobenzene.[65]

Diethylzinc can also function as a base, deprotonating ammonia, aniline, dimethylamine, oxamide, and acetamide to give the Zn−N derivatives.[66] Of particular utility is the alkylation by zinc alkyls, including diethylzinc, of tertiary alkyl chlorides to give tetralkylmethanes, R_4C, in moderate yield.[67]

Thus, the synthetic utility of the dialkylzincs had been demonstrated, but since 1900, with the advent of the Grignard reagents, they received much less attention and utilization. However, in recent years there has been a renaissance in dialkylzinc chemistry. A report in 1984[68] that the reaction of dimethylzinc with benzaldehyde, when carried out in the presence of a catalytic quantity of (*S*)-leucinol, gave PhMeCHOH after hydrolysis with moderate (49% ee) enantioselectivity was responsible for this new interest in dialkylzincs. Noyori and co-workers[69] followed with a better catalyst, (−)-3-*exo*-dimethylaminoisobornenol, the use of which resulted in formation of PhMeCHOH in up to 95% ee. Enantioselective alkylation of aldehydes by dialkylzinc reagents has been a very active area of research ever since, and it has been reviewed this year.[70] (See also the organozinc chapters in the first[71] and second[72,73] editions of *Comprehensive Organometallic Chemistry*, as well as other book chapters and reviews.[74−80]) A recent book is devoted wholly to the applications of organozinc reagents in organic synthesis.[81]

An important property of the dialkylzincs is their functional group tolerance compared to Grignard and organolithium reagents. This makes them the reagent of choice when other functional groups that are prone to attack by strong nucleophiles are present in the electrophilic substrate. A recent example in which diethylzinc was the preferred alkylating agent is the zirconium isopropoxide catalyzed imine alkylation by diethylzinc, which was promoted by peptide-based chiral ligands.[82]

Thus, Frankland's dialkylzinc compounds have turned out to be useful synthetic reagents in the present time. However, in the direct RI/Zn reaction, the first product formed is the alkylzinc iodide RZnI. Frankland, in his early work, did not recognize CH_3ZnI and C_2H_5ZnI as discrete compounds and did not study or utilize them further. Later workers, however, developed the RZnX compounds as useful reagents in organic synthesis. These studies were carried out after the development of the Grignard reagents and, like the RMgX species, the RZnX compounds usually were prepared in solution by the reaction of an organic halide with zinc (as a copper couple or activated in some way, vide supra) and used in the subsequent reaction with the electrophilic substrate without priori solation. Thus, Arthur Michael in 1901 reported preparing C_2H_5ZnI by the reaction of ethyl iodide with zinc in refluxing diethyl ether under an atmopshere of CO_2 and adding benzoyl chloride to the resulting solution. Aqueous workup gave ethyl phenyl ketone in 30% yield:[83]

$$C_2H_5ZnI + C_6H_5C(O)Cl \rightarrow C_6H_5C(O)C_2H_5 + ZnICl \quad (8)$$

Diethyl ketone was reported to have been prepared in this way in "better yield". Michael remarked "It seems to have been overlooked that this substance [i.e. C_2H_5ZnI] may be used in many of the preparations which involve the use of zinc ethyl [i.e., $(C_2H_5)_2Zn$] ..." Blaise recognized this as a potentially useful, general ketone synthesis and developed it into a reproducible, high-yield procedure[84] which came to bear his name. Blaise wrote the ethereal alkylzinc iodide as **1**, in analogy to a then-current (but wrong) formulation of the ethereal Grignard reagent. Later workers showed that solvents

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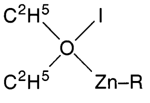

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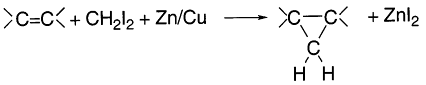
other than ethers could be used in the preparation of alkylzinc halides: ethyl acetate,[85] *N*,*N*-dimethylformamide,[86,87] 1,2-dimethoxyethane and diglyme,[77] dimethyl sulfoxide,[87,88] diethyl carbonate,[88] tributyl phosphate,[88] and sulfolane.[88]

Current interest in alkyl- as well as arylzinc halides is due to the discovery that they undergo facile cross-coupling with aryl and vinyl halides in the presence of a suitable palladium catalyst, a reaction developed by Negishi:[89]

$$\mathrm{RZnX + CH_2{=}CHX \rightarrow R{-}CH{=}CH_2 + ZnX_2} \quad (9)$$

This reaction usually worked satisfactorily only with aryl and vinyl bromides and iodides, but a palladium catalyst, $Pd(CMe_3)_2$, has been found that is effective also with aryl and vinyl chlorides.[90]

One alkylzinc iodide merits special mention because its applications in synthesis are 3-fold: as a methylene transfer agent, as an olefination agent, and as a source of the nucleophilic CH_2I group. In 1929, Guy Emschwiller reported the preparation of iodomethylzinc iodide by the reaction of diiodomethane with a Zn/Cu couple.[91] Its hydrolysis was slow and gave methyl iodide and its iodinolysis, diiodomethane; it decomposed slowly in diethyl either solution at room temperature to give ethylene and ZnI_2. It apparently did not undergo the Blaise reaction with acetyl chloride and so was of no further interest—until 1958, when H. E. Simmons and R. D. Smith of Du Pont reported that ICH_2ZnI prepared in situ reacts with olefins in refluxing diethyl ether to give cyclopropanes[92] (eq 10). Further studies by Blanchard and Simmons[93] established that this reaction did not proceed via free CH_2 as an intermediate; rather, a kinetically bimolecular process was involved in the CH_2 transfer from zinc to the olefin. It was suggested that the species in solution was "$Zn(CH_2I)_2{\cdot}ZnI_2$" rather than ICH_2ZnI. This appears to be the case in acetone solution, according to later studies by Denmark et al.[94] The "Simmons–Smith reaction" found immediate (and finds continuing) application in the synthesis of cyclopropanes. A significant improvement of the original Simmons-Smith procedure was reported by Repič and Vogt.[95] Ultrasonication activates zinc (without the need of a Zn/Cu couple) so that it reacts rapidly and exothermally with CH_2I_2 in the presence of olefins to give high cyclopropane yields.



$$\mathrm{{>}C{=}C{<} + CH_2I_2 + Zn/Cu \longrightarrow {>}\underset{\underset{H\ \ H}{C}}{C{-}C}{<} + ZnI_2} \quad (10)$$

In another improvement, the Simmons–Smith reaction can be carried out in homogeneous solution in procedures developed by two Japanese groups. In one of these, CH_2I_2 was added to a mixture of 1 molar equiv each of the olefin and diethylzinc in a hydrocarbon solvent to give a soluble iodomethylzinc reagent[96] (eqs 11 and 12). This variation of the original Simmons–Smith reagent is easier to carry out, it is more reproducible, and the reactions with olefins are more rapid and give better yields of cyclopropanes. The $(C_2H_5)_2Zn/CH_2I_2$ or CH_2ClI reaction was found to be a free radical process, accelerated by oxygen and UV radiation.[97] The second procedure uses the reaction of C_2H_5ZnI with CH_2I_2.[98] The authors suggested that $C_2H_5ZnCH_2I$ is the intermediate which is formed, although formation of ICH_2ZnI and C_2H_5I seems more likely. In any case, these homogeneous procedures are faster than the CH_2I_2 + Zn/Cu procedure and generally give better cyclopropane yields. A less practical route to iodomethyl- and chloromethylzinc compounds was reported by Wittig and co-workers: the reaction of diazomethane with ZnI_2 and $ZnCl_2$.[99] The $Zn(CH_2X)_2$ thus prepared reacted with cyclohexene, giving norcarane in moderate yield.

$$\mathrm{CH_2I_2 + (C_2H_5)_2Zn \rightarrow C_2H_5I + C_2H_5ZnCH_2I} \quad (11)$$

$$\mathrm{CH_2I_2 + C_2H_5ZnCH_2I \rightarrow C_2H_5I + Zn(CH_2I)_2} \quad (12)$$

The CH_2I_2– and CH_2Br_2–Zn/Cu couple reagents insert CH_2 into the Si–H bond of triorganosilanes in a reaction that is much faster than the cyclopropanation of olefins under the same conditions with these reagents:[100]

$$\mathrm{CH_2I_2 + Zn/Cu + (C_2H_5)_3SiH \xrightarrow{Et_2O} (C_2H_5)_3SiCH_3 + ZnI_2} \quad (13)$$

The $(C_2H_5)_2Zn/CH_2I_2$ reagent showed similar reactivity toward organosilicon hydrides.[101] A direct, bimolecular CH_2 insertion into the Si–H bond, as in the case of the olefin cyclopropanation reaction, seems to be operative.

In a second type of reactivity, the iodomethylzinc compounds can serve as carbonyl methylenation re-

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agents.[102] Thus, reaction of benzaldehyde with the CH_2I_2 or $CH_2ClI-Zn/Cu$ reagent in the presence of an excess of zinc in THF at 35 °C gave styrene in good yield. This reaction is facilitated by ultrasonication, proceeding more rapidly in THF at room temperature.[103] It gives good yields of terminal olefins with aldehydes but not with ketones.

Finally, the iodomethylzinc iodide reagent (prepared by the $C_2H_5ZnI + CH_2I_2$ procedure) can react as a nucleophilic source of the CH_2I group in reactions with potent electrophiles such as organotin, organolead, and mercuric halides.[104a] (eqs 14 and 15). The iodomethyltin

$$ICH_2ZnI + (CH_3)_3SnCl \rightarrow (CH_3)_3SnCH_2I + ZnClI \quad (14)$$

$$2\ ICH_2ZnI + HgI_2 \rightarrow Hg(CH_2I)_2 + ZnI_2 \quad (15)$$

and iodomethylmercury product yields were high.

Diethylzinc and ethylzinc iodide react with other *gem*-diiodoalkanes to give α-iodoalkylzinc iodide, whose reactivity parallels that of ICH_2ZnI. Prepared in this manner have been $CH_3CHIZnI$,[105] $(CH_3)_3SiCHIZnI$,[104b] and $(CH_3)_3SnCHIZnI$.[104b]

While most preparations of RZnX compounds use the RX + activated Zn reaction, an alternate procedure is based on the redistribution reaction between a dialkylzinc and a zinc halide (eq 16). An *Organometallic*

$$R_2Zn + ZnX_2 \rightarrow 2RZnX \quad (16)$$

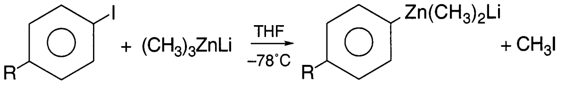
Syntheses procedure for C_2H_5ZnCl is available.[47] This procedure was used first by Wanklyn in 1861, who mentioned that "the iodide of zinc forms with zinc-methyl a crystalline compound of great beauty."[35]

In conclusion, one other type of alkylzinc compound should be mentioned: the tri- and tetraalkylzincates. The first of these, $NaZn(C_2H_5)_3$, was reported by Wanklyn in 1858.[106] This compound was discovered during his attempts to prepare ethylsodium by the reaction of ethyl iodide with sodium in diethyl ether. Wanklyn had found that sodium and potassium decomposed diethylzinc. In a subsequent experiment, he sealed up a piece of sodium and 10 times its weight of diethylzinc under coal gas in a glass tube and cooled the contents in cold water with occasional shaking. Within a few days, the sodium became coated with zinc and slowly was consumed. A solid and a viscous liquid remained. After a few days, the tube contained metallic zinc and a clear, colorless liquid. When the tube was opened, the amount of zinc was found to be equivalent to that of the sodium used. Wanklyn believed the liquid to be a solution of ethylsodium in diethylzinc. It was pyrophoric in air (burned explosively, he said) and was most difficult to handle. When the liquid was cooled to 0 °C, a large quantity of crystals formed; evaporation of the supernatant liquid in a stream of hydrogen left a crystalline solid. Analysis of the crystals proved to be very difficult because of their great air sensitivity, but Wanklyn arrived at the formula

$$\left.\begin{matrix}\mathrm{Na}\\ \mathrm{C_4H_5}\end{matrix}\right\} + 2\left\{\begin{matrix}\mathrm{Zn}\\ \mathrm{C_4H_5}\end{matrix}\right.$$

which, using current atomic weights, translates as $NaZn(C_2H_5)_3$. Wanklyn tried very hard, but without success, to extract ethylsodium from this product. The reaction of potassium and lithium with diethylzinc gave similar products. Wanklyn had discovered the organometallic metal displacement reaction. He realized this and suggested that it should be a general reaction (which indeed it is).

Such a new type of compound was intriguing, and Wanklyn studied its reactivity. It was readily hydrolyzed and reacted with CO_2 (not an inert gas here as it is toward diethylzinc) to give, after hydrolysis, propionic acid.[107] The methyl analogue, $NaZn(CH_3)_3$, reacted with CO_2 to give acetic acid.[108] Heating a mixture of $NaZn(C_2H_5)_3$ with metallic mercury and zinc at ~100 °C resulted in formation of sodium amalgam and the release of diethylzinc. The same reaction, but with magnesium rather than zinc, gave $Mg[Zn(C_2H_5)_3]_2$.[109] An interesting reaction occurred when $NaZn(C_2H_5)_3$ and carbon monoxide were sealed in a glass tube and heated at 100 °C.[110] Metallic zinc was formed. The organic product was $(C_2H_5)_2CO$—a novel ketone synthesis. Later workers found that alkali-metal trialkylzincates undergo 1,4 (conjugate) addition to α,β-unsaturated ketones.[111] In another application, $LiZn(CH_3)_3$ underwent iodine−zinc exchange with aryl iodides[112] (eq 17).



(17)

Very careful, very thorough physical chemical studies were carried out by Franz Hein and his students on the alkali-metal trialkylzincates in the 1920s.[113] By now, various types of Schlenk apparatus and techniques were available which facilitated such studies with these very air-sensitive compounds. Conductivity studies of molten (mp 27 °C) $NaZn(C_2H_5)_3$ established its salt-like character, $Na^+[Zn(C_2H_5)_3]^-$. Other salts, $M[Zn(C_2H_5)_3]$ (M = K, Rb), as well as $R_4N^+[ZnI(C_2H_5)_2]$, were prepared by reaction of diethylzinc with MC_2H_5 (now known compounds) or $[R_4N]I$. $[(C_2H_5)_3Zn]^-$ was transported to the anode on electrolysis, and the disproportionation products of the ethyl radical, C_2H_6 and C_2H_4, were formed. When a lead anode was used, tetraethyllead

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was formed. Molar conductivities in $(C_2H_5)_2Zn$ solution at 50 °C were as follows: LiC_2H_5, 0.13; NaC_2H_5, 4.01; KC_2H_5, 6.49; RbC_2H_5, 9.39 Ω^{-1} cm^{-1}. The solutes were more complicated than $M[Zn(C_2H_5)_3]$, since molecular weight determinations showed concentration-dependent association to occur: X-ray crystal structure determinations of higher sodium and potassium trialkylzincates, $M[ZnR_3]$ (M = Na, K; R = $CH_2C(CH_3)_3$) and $K[Zn(CH_2SiMe_3)_3]_3$, have shown the presence of discrete M^+ and $[ZnR_3]^-$ ions, associated with $\{M[ZnR_3]\}_2$ dimers.[114] However, it is not completely certain what species are present in solution. Jander and Fischer[115] rationalized the observed concentration dependence of the conductivity of solutions of ethyllithium in diethylzinc in terms of associated species (as suggested by Hein), writing the equilibria

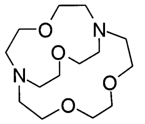
$$C_2H_5Li + (C_2H_5)_2Zn \rightarrow C_2H_5Li + (C_2H_5)_2Zn \rightleftharpoons Li^+ + [Zn(C_2H_5)_3]^-$$

$$2C_2H_5Li \rightarrow (C_2H_5)_2Zn \rightleftharpoons [C_2H_5Li \rightarrow (C_2H_5)_2Zn]_2 \rightleftharpoons Li^+ + [LiZn_2(C_2H_5)_6]^-$$

$$[LiZn_2(C_2H_5)_6]^- \rightleftharpoons Li^+ + [Zn_2(C_2H_5)_6]^{2-}$$

In dilute solution, it was suggested, the complex $(C_2H_5Li \rightarrow (C_2H_5)_2Zn)$ was present, whose dissociation to $Li^+[Zn(C_2H_5)_3]^-$ increases with increasing dilution. However, ^7Li and ^1H NMR studies of the $C_2H_5Li/(C_2H_5)_2Zn$ systems in diethyl ether solution were interpreted in terms of the presence of $Li_2Zn(CH_3)_4$ and $Li_3Zn(CH_3)_5$ but not of $LiZn(CH_3)_3$.[116] Hurd had reported $Li_2Zn(CH_3)_4$ in 1948,[117] and Weiss and Wolfrum[118] were able to isolate it as a pyrophoric, crystalline powder and determine its structure by powder X-ray diffraction. The crystals contain distorted tetrahedral $[(CH_3)_4Zn]^{2-}$ ions (d(Zn−C) = 2.07 Å) and Li^+ cations. The C−Li interactions (d(Li−C) = 2.84, 2.52 Å) are weaker. Compounds of the type $MZn(C_2H_5)_4$ (M = Ca, Sr, Ba) also are known.[119]

Finally, there are some interesting compounds that contain a $[C_2H_5Zn]^+$ cation.[120] When a benzene solution containing equimolar amounts of $(C_2H_5)_2Zn$, $(C_2H_5)_3Al$, the and 1,1,2-cryptand **C** is prepared, a small dense liquid phase separates that contains $C_2H_5Zn\mathbf{C}^+$ and $(C_2H_5)_4Al^-$. When Ph_2Zn is used instead of triethylaluminum, the product contains an organozinc cation and a zincate anion: $[C_2H_5Zn\mathbf{C}]^+[Zn(C_2H_5)(C_6H_5)_2]^-$. On the other hand, combination of $(C_2H_5)_2Zn$, $(C_2H_5)_2Mg$, and the cryptand in benzene results in formation of a magnesium cation and a zincate anion, $[C_2H_5Mg\mathbf{C}]^+[Zn(C_2H_5)_3]^-$.



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Epilogue

We have followed our cover molecules as well as their methyl analogues from their discovery in 1849 to the present day, 152 years later. At the beginning, they were the only available sources of nucleophilic alkyl groups. When the more reactive Grignard reagents came onto the scene, they went into a decline. Now, however, they are flourishing again, having found new uses in important synthetic processes. They are air- and moisture-sensitive, but modern handling techniques can deal with that. They are less reactive than the Grignard and organolithium reagents, but for some purposes this can be an advantage. Also, they are not toxic, nor are the inorganic zinc products of their reactions, and in these days, where environmental concerns loom large, this is important. Frankland's discovery has borne bountiful fruit. It led not only to the development of organozinc chemistry: it gave birth to the whole vast field of organometallic chemistry and led also to the concept of valency.

Frankland devoted only some 15 years of his career to organometallic chemistry. Part of this time was spent in places with poor facilities for chemical research and with few, if any, co-workers, which makes his achievements all the more remarkable. One wonders what else he might have done to further develop this new area of chemistry if he had not left his research in organometallic chemistry for activities in other areas.

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