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Perspective

Crystal Engineering in Kindergarten[1]

Bart Kahr*

Department of Chemistry, University of Washington, Box 351700, Seattle, Washington 98195-1700

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ABSTRACT: Friederich Froebel, a nineteenth century educator trained as a crystallographer, invented kindergarten. Froebel's background in crystallography infused every aspect of his conception of kindergarten, especially the self-actuated learning devices or "gifts" that were the centerpiece of his curriculum. Froebel kindergartens spread rapidly throughout Europe, the United States, and Japan in the latter half of the nineteenth century. Crystal engineering was thus a primary occupation of millions of children in the first several kindergarten generations.

Introduction

As I was strolling through a local bookstore during the week that my son began attending a Seattle public kindergarten, my eye was drawn to a smart looking volume called *Inventing Kindergarten* by Norman Brosterman.[2] Inside, I discovered that kindergarten, an institution to which I had given little thought since my own experience as a kindergartner,[3] was the deliberate invention of a crystallographer, Friederich Froebel (1782−1852; Figure 1). Froebel's kindergarten was a direct outgrowth of his experience handling crystals as an assistant to the great Christian Samuel Weiss (1780−1856), the inventor of the concept of the crystallographic system. Froebel believed that the strongest start for young minds was training in the principles of point and translational symmetry, adapted for youngsters through various polyhedra and lattice building devices that would enable recognition and appreciation of "natural harmonies." According to Froebel, crystal engineering was best begun by children not long out of diapers.

Rubin, who first recognized that the "Professor Weiss" in Froebel's autobiography was the famous Christian Samuel, established the Froebel crystallography connection.[4] While some aspects of symmetry that can be explored with Froebel's gifts had already been articulated in the design literature,[5,6] they have never been illustrated for crystallographers, by a crystallographer, or in a crystallographic forum. I was astonished, as likewise I expect some of my colleagues to be, to learn that children in an Atlanta kindergarten at the turn of the century could be found playing with blocks in such a manner in a room otherwise unadorned save for a portrait of a nineteenth century German crystallographer (Figure 2).

Figure 1. Portrait of Froebel on a German postage stamp.

During the preparation of this article, Rubin published a book about Froebel, his crystallographic influences, and the influence of his kindergarten on modern artists: *Intimate Triangle: Architecture of Crystals, Frank Lloyd Wright, and the Froebel Kindergarten*. It would be all too easy to overlook *Intimate Triangle*, a modest volume in appearance, published by Polycrystal Book Service,[7] in favor of *Inventing Kindergarten*, a richly illustrated and artfully designed book in keeping with the high standards of its publisher, Harry N. Abrams. However, Rubin's book is based upon 30 years of original and painstaking research, some of which

* E-mail: kahr@chem.washington.edu.

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Figure 2. Atlanta kindergartners c. 1900 with a portrait of Froebel (The Library of Congress, Washington, DC). From ref 2, p 94. Copyright 2002 Harry N. Abrams.

made its way into *Inventing Kindergarten*. *Intimate Triangle* has a more consistent crystallographic focus, whereas Brosterman's book is closer to a general history. I recommend them both with great enthusiasm to any crystallographer.

Early Life. Friederich Froebel was born in central Germany. As a young boy, he explored its forests and countryside. His mother died during his infancy and his father, a Lutheran minister, had little time for the boy. Friedrich spent his adolescence with an empathetic uncle after which time he was apprenticed to a woodsman with a modest library. An autodidact, he studied botany and geometry. After two years, Froebel persuaded his father to allow him to join his older brother at the university in Jena so that he could formalize his education and satisfy his growing curiosity about the natural world. He took pleasure in courses in mineralogy, chemistry, physics, biology, mathematics, languages, architecture, and land surveying, but also spent several months in jail for nonpayment of rent after his modest assets expired. Froebel then reluctantly took a course in practical farming at the urging of his father who died shortly thereafter. Released from this obligation, Froebel tried his hand at land surveying in Frankfurt-am-Main; he wished for an eventual career in architecture.

Taking another turn, Froebel joined the Frankfurt Model School as a teacher in 1805. This unusual institution was founded by a disciple of Johann Pestalozzi, a revolutionary Swiss educator who emphasized the importance of active learning based upon observation and hands-on experience in place of lectures, recitations, and floggings. Beginning in 1808, Froebel spent two years in Yverdon with Pestalozzi to internalize the master's philosophy. Ever restless, he then enrolled in the University of Göttingen in 1811 to study physics, chemistry, and mineralogy, possibly motivated by the strength given to the atomic theory by the recent publications of John Dalton and Joseph Gay-Lussac. Here, we see Froebel oscillating between natural science and education. This pattern will be repeated. Once again, his studies were interrupted, this time by a tour in the Prussian army that ended with Napoleon's defeat in 1814.

Crystallographic Apprenticeship. Unnamed "influential friends" had promised Froebel a post after the war as assistant to Weiss[8] in the Mineralogical Museum at the University of Berlin. Weiss contributed to the classification of crystals by de-emphasizing the preeminence of cleavage shaped molecules in favor of growth directions. He created crystal systems in terms of axial intercepts of developed facets, a precursor of the Miller system. He faltered in his overemphasis of orthogonal axes; the monoclinic and triclinic systems were considered as hemihedral manifestations of orthorhombic. Furthermore, he insisted that axial ratios were inverses of the square roots of sums of squares of integers.[9] This insistence stemmed from a mystical or romantic belief in numerology in preference to experiment. He ignored the revelations of angle variation with temperature by Franz Neumann and with composition by Eilhard Mitscherlich.[10]

In Berlin, Froebel sat day after day in a quiet room cataloging minerals. "While engaged in the work," he said,

> I continually proved to be true what had long been a presentiment with me, namely, that even in these so-called lifeless stones and fragments of rock, torn from their original bed, there lay germs of transforming, developing energy and activity. Amidst the diversity of forms around me, I recognised under all kinds of various modifications one law of development...And thereafter, my rocks and crystals served me as a mirror wherein I might descry mankind, and man's development and history ...Geology and crystallography not only opened up for me a higher circle of knowledge and insight, but also showed me a higher goal for my inquiry, my speculation, and my endeavour. Nature and man now seemed to me mutually to explain each other, through all their numberless various stages of development.[11]

It was during his time with Weiss that he was awakened to "the conviction of an inner demonstrable connection in all cosmical development."[12] If the reader is beginning to suspect that Froebel's philosophy of spiritual crystallography is sometimes incoherent I can confirm that this is so and offer his following passage in evidence.

> There is a very remarkable analogy between the development of crystalline forms in nature and that of human intelligence and feeling. Like the crystal, man, though he bears a vital unity within him, at first shows in his actions one-sidedness and individuality, and only later rises to harmony and completeness. The recognition of this similarity is most helpful and enlightening in gaining a knowledge of self, in cultivating strength of will and confidence in action, and so in educating both oneself and others. Like the world of intellect and feeling, the world of crystalline forms is a glorious and instructive world. It shows in outward guise what in the former realm lies open only to the spiritual gaze.[13]

Froebel admitted to being a poor writer[11] and others have said as much.[25] Nevertheless, a consistent philosophy can be distilled from his writings taken as a whole. This is achieved by Snider, one of many Froebel biographers, who well summarized the critical 1814–1816 period with Weiss:

> Little society [Froebel] has except the crystal, he becomes a crystal himself, and learns its speech. So thoroughly does he sink himself in this occupation that his soul gets a distinct crystallographic bent which lasts through life and is seen in all his schemes of education. Going day after day into his chamber of crystals, as if into a cave of stalactites, he examines, fondles, and labels his specimens, he himself being the most remarkable specimen of the lot....The crystallographer secretly works away in his chamber, like a crystal slowly and quietly forming itself. He sees nature shooting into right lines out of chaos, thus she begins to take on her forms. He is working back to the primitive cosmical energy and beholding the universe organize itself. All of this he will hereafter apply to the unfolding of man, and specially of the child, who also begins with an inner chaos which must organize itself mainly through education.[12]

Froebel believed that since the same laws of nature governed the growth of crystals, flowers, children, and societies, the most efficacious way of intuiting the logic of creation was through manipulating and copying crystals, the simplest of the forms that were easily comprehended in terms of relatively simple mathematical principles. He said, “The simplest forms, which lie at the foundation of the fabric of the world, lay also the foundation in the minds of children for the understanding of the world, which expresses God’s thought. These simplest and unarticulated forms are the fundamental forms of crystallization.”[17]

In 1816, Froebel was offered a professorship in Stockholm. Here, he would undoubtedly have interacted with Sweden’s greatest scientist, Jöns Jakob Berzelius, who made enormous contributions to the classification of crystals according to composition.[14] We know very little about the offer of this position, but it may well have been extended by Berzelius, whose extensive mineral classification had been just published in 1815.[15] Berzelius was president of the Swedish Academy of Sciences, and it is unlikely that Froebel would have been invited to Stockholm without Berzelius’s knowledge and consent. Nevertheless, Froebel declined this remarkable opportunity. He recorded his change of heart and in so doing strikes an all too familiar chord:

> It had long been my dearest wish to devote myself to an academic career, for I thought to find in it my vocation, the meaning of my life. But the opportunity to get to know students and see their slight knowledge of the subject, their small feeling for it, and still more their lack of any true scientific spirit made me go back on my purpose. I became all the more strongly aware of man’s claims to a life which should express his essential being, and so I began to think earnestly again about education and teaching. Therefore, I stayed in my post only for two years, but meanwhile the stones in my hand and under my eyes became forms of life which spoke a language I understood. The world of crystals clearly proclaimed the structure of man’s life to me and spoke of the real life of his world.[16]

According to Brosterman, it was during the period from 1814 to 1816 that through his “daily work with crystals, Froebel’s two major interests, nature and education, finally intersected in a cohesive and easily demonstrable fashion that would result, many years later, in the creation of the first kindergarten.”[2]

The Kindergarten and its “Gifts”. Froebel passed up Stockholm in favor of starting a school for small children, The Universal German Educational Institute that operated until 1831. This was not a kindergarten; it enrolled students at age seven as was common in Prussia. But during this time Froebel began to codify his educational philosophy, particularly in *Education of Man* (1826),[17] which began to attract supporters in the education establishment.

In 1837, Froebel opened his first school for early childhood education. Two years later he coined *Kindergarten*, a welcome replacement for *Kleinkinderbeschaftigungsanstalt* (institution where small children are occupied).[18] Here, he introduced a curriculum based upon his so-called 20 “gifts”, a set of geometrically oriented toys and crafts through which the child was intended to develop an “inner connection” with the objects he or she studies.

The gifts were special balls, blocks, sticks, and paper that were manufactured and widely distributed by the Milton Bradley and J. W. Schermerhorn companies among others. The first gift was a set of brightly colored woolen balls on strings. The second was a set of three shapes cut from maple, the sphere, cylinder, and cube. These solids were bored with holes fitted to dowels that would enable the child to transform the shape under investigation by spinning. The cube, for example, was bored through opposite edges, corners, and faces, thus providing an intuitive sense of the distinction between 2-, 3-, and 4-fold rotation axes, and the increase in symmetry that results from dynamic processes. The third gift was a set of building blocks. A cube was divided through three perpendicular planes into eight similar cubes. Froebel expressed an appreciation of Réné Just Häuy’s understanding of the crystal form in terms of aggregates of the so-called *molecule integrante*:

> The child thus distinguishes here as a given fact...a whole and a part, for each component cube is a part of the principal cube. The component cubes have the same form as the principal cube; thus what the principal cube shows once in respect to its form, the component cubes show together as often and as repeatedly as there are cubes...He thus again distinguishes purely as a perceptible fact the size from the form, for each component cube shares indeed the cubical form of the principal cube, but not its size...By this simple play the above-mentioned fundamental perceptions, whole and part, form and size, are made clear by comparison and contrast and deeply impressed by repetition.[13]

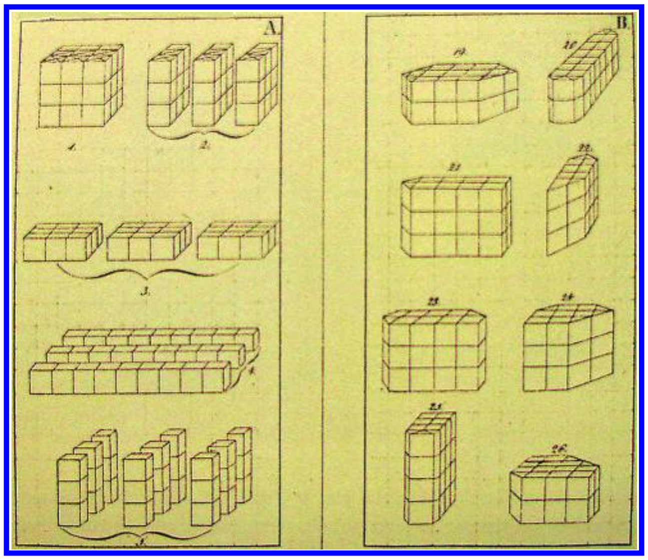

Figure 3. Building blocks. (Frobel, F. *Ein Sontagsblatt für Gleichgesinnte*, 1838–1840). From ref 2, p 57. Copyright 2002 Harry N. Abrams.

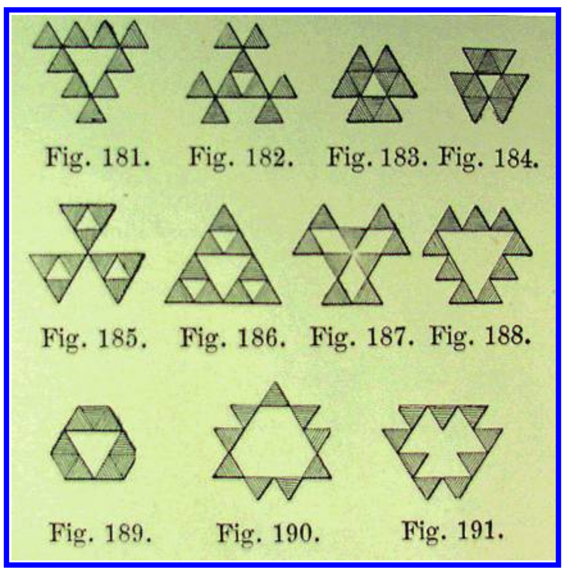

Figure 4. Distinct decorations with nine equilateral triangles.[20]

The fourth gift consisted of a set of eight rectilinear blocks with sides in a ratio of 1:2:4 that also formed a cube when stacked. The fifth and sixth gifts introduced cubes cut along the face diagonals in halves and quarters (Figure 3). Economou used the third through sixth gifts as a means of introducing the concepts of permutation groups and conjugacy classes.[19]

The seventh gift was parquetry. It consisted of sets of colored square and triangular tiles (right, equilateral, and isosceles) that encouraged explorations in tiling the plane (Figure 4).

There is no need to comment on each of the 20 gifts in succession. Such discussions can be found in Brosterman,[2] Rubin,[7] or Wiebé.[20] The 14th gift, braidings with strips of paper, is of particular crystallographic interest because it introduced students to plane groups, and even color symmetry.

According to Wiebé:

> Braiding satisfies the taste of color, because to each piece of braiding, strips of at least two different colors belong. It excites the sense of beauty because beautiful, i.e., symmetrical, forms are produced...The sense and appreciation of number are constantly nourished, nay it may be asserted, that there is hardly a better means of affording perceptions of numerical conditions, so thorough, founded on individual experience and rendered more distinct by diversity in form and color.[20]

In Figure 5a, we see the tools used in the Froebel braiding scheme. It illustrates the simplest braid, which would correspond to the plane group $p4mm$ if the white spaces are taken as voids. If the white spaces are considered as anti-equal, we would classify it according to the two color symmetry group $p4'm'm'm$ in which each primed symmetry operation exchanges black and white tiles. Although antisymmetry groups[22] were not enumerated until the independent work of Heesch[23] and Shubnikov,[24] Froebel's disciples appreciated the tension intrinsic to tiling with two colors. Wiebé called antisymmetric squares "oppositionally alike". He was explicit in trying to enumerate the distinct tilings that could be achieved through periodic sequences of up and down moves. Moreover, he recognized that rectilinear unit cells were not requisite (Figure 5b).

The penultimate gift was the so-called "peas work", an ancestor of molecular model kits (Figure 6). Here, softened peas or corks served as connectors for toothpicks in constructions both abstract and representational. The kits, sold by A. N. Myers and Co. in London, were accompanied by cards that illustrated bridges, buildings, and crystalline polyhedra.

The last gift was modeling clay. The child was entreated to deform a sphere until it became a cube and by "continued change of edges to planes and planes to corners, the most important regular forms of crystallization will be produced."[20]

The Kindergarten Movement. By 1847, Froebel ran seven kindergartens with the help of energetic female colleagues who seized upon early childhood education as remedy for their own disenfranchisement within the rigid Prussian society. Among these was Baroness Bertha von Marenholtz-Bülow who arranged a mansion for Froebel to use for the training of kindergarten teachers.[25]

Sadly, by 1851, just when Froebel's kindergarten program seemed to be gaining momentum, the Prussian court outlawed kindergarten teaching. Rocked by the pro-democracy revolts of 1848, officialdom was suspicious of kindergartens in which Froebel sought to give unfettered reign to the "free republic of childhood." Brokenhearted, Froebel died in 1852. While the kindergarten movement was temporarily squelched in Germany, it was well on its way to becoming established throughout the world in large measure because women saw kindergarten as a way of undermining those institutions that fostered their intellectual subjugation while at the same time creating new professional opportunities. The Baroness was an indefatigable traveling champion of the kindergarten movement, and many other converts carried her torch.

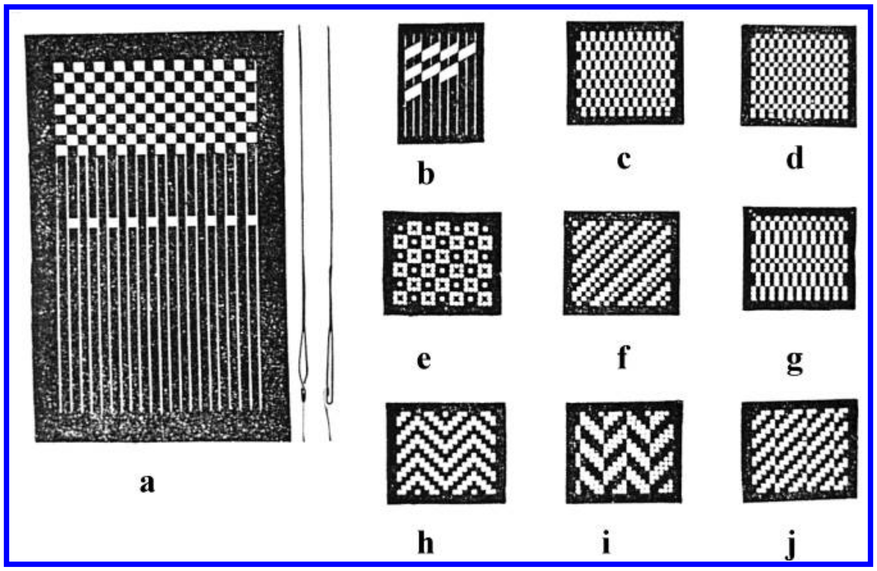

Figure 5. Examples of braiding. (a) Slatted base in black paper is threaded with white strips using the needles indicated producing a tetragonal tiling. Shubnikov layer group with anti-symmetry is $p4'm'm'm$. The same symmetry with a different decoration is shown in (e). (b) An oblique lattice. (c, d) Twofold anti-symmetry operations. (f) Polar axis in mirror symmetric tiling. (g) Proto aperiodic or complex periodic tiling. (h) Mirror with antisymmetric glide. (i) Mirror antisymmetry with glide. (j) Twofold and anti-2-fold symmetry.[20]

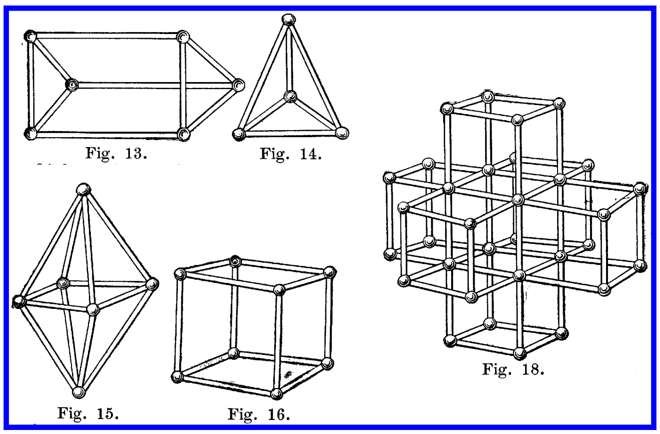

Figure 6. Peas work.[20]

The first English kindergarten was established in London in 1851, and the first in the United States opened in Watertown, Wisconsin, in 1856. The Watertown kindergarten, just a short ride from the home of Anna Lloyd Jones, the mother of Frank Lloyd Wright, is widely believed to have altered the course of modern architecture (see below). By 1885, there were 545 American kindergartens (see for example Figure 7). By 1879, 65% of Parisian children were enrolled in Froebel classes. Von Marenholtz-Bülow left kindergartens in her wake in Vienna (1857), Amersterdam (1858), Neuchâtel (1862), and Venice (~1865), among many other cities. By 1875, Holland had 2,222 kindergarten teachers (98% women). In 1883, Geneva had 55 Froebel kindergartens; St. Petersburg had 26 by 1890. By 1911, there were more than 45,000 kindergartners in Japan. Froebelian kindergartens even prospered in Germany, despite the blow delivered by the ban (later revoked). There were some 2,000 by 1887.[26]

Excellent kindergarten manuals were published in the nineteenth century which encouraged the spread of Froebel's philosophy and methodology. Especially influential was Wiebé's *Paradise of Childhood*[20] in which,

Figure 7. St. Louis, Missouri kindergarten, c. 1875. Under the portrait in the Froebel shrine to the left is the motto, "Let us live for the children". (Photo exhibited by Susan Blow at the 1876 Philadelphia Centennial Exposition. From ref 2, p 91). Copyright 2002 Harry N. Abrams.

Brosterman remarks, "kindergarten's crystalline vocabulary became essentially fixed."[2]

Kindergarten and Modern Artists. Frank Lloyd Wright was introduced to Froebel's methods of design by his mother who was in contact with the foremost American kindergarten pioneers in Wisconsin and Boston. Wright emphatically and repeatedly remarked on the formative influences of his experience with Froebel's gifts and occupations.[27] For example,

> The poet's message at heart, I wanted to go to work for the great moderns...and finally I went...armed with the Froebel-kindergarten education I had received as a child from my mother. Early training which happened to be perfectly suited to the T-square and triangle technique now to become a characteristic, natural to the machine-age...In the Frederick Froebel Kindergarten...mother found the 'Gifts'.

> And 'gifts' they were. Along with the gifts was the system, as a basis for design and the elementary geometry behind all natural birth of Form.

Architectural historians have traced Wright's revolutionary architectural style to Froebel's "spiritual geometry." Rubin and Brosterman go further in arguing that not only Wright, but many of the pioneers of modern art and architecture had similar experiences and influences. Millions of children in the half-century preceding World War I were exposed to Froebel's methods throughout the world. Our authors persuasively argue that the Froebelian system was a force that led to modernism, the general revolution in art and architecture brought forward by kindergarten graduates. Besides Wright, Le Corbusier, Paul Klee, Walter Gropius, Josef Albers, Wassily Kandinsky, Piet Mondian, and Georges Braque, among other pioneers, likely attended Froebel, or Froebel-inspired kindergartens. When comparing the art of American kindergartners c. 1875−1910 with similar constructions by famous artists that are reproduced side by side in Brosterman's book, the case is compelling indeed that Froebel laid the groundwork for the wholesale overthrow of convention in Western art during the first decade of the twentieth century.

Kindergarten and Modern Crystallographers. In the prologue to *Inventing Kindergarten*, Brosterman quotes Virginia Woolfe, who, in response to an exhibition of Post-Impressionist painting said, "On or about December 1910, human character changed."[28] While she was talking about art, it has frequently been pointed out that the sciences of space, matter, and time were similarly and contemporaneously transformed. The special theory of relativity, the quantum theory of radiation, and the first models of the atom date from the first decade of the twentieth century. Crystallography also underwent a change of character at about this time. Max von Laue discovered X-ray diffraction in 1912, and subsequent crystal structure determinations showed without doubt that the external manifestations of crystals were a result of the internal forces acting on the constituent ions and molecules. The Braggs's determination of the structure of sodium chloride in 1913[29] is arguably the *Les Demoiselles d'Avignon* (Pablo Picasso, 1907) of crystallography.

If many of the pioneering artists had their geometric sensibilities inculcated in Froebel kindergartens, it is likely that many of the pioneering X-ray crystallographers had a similar experience. Did the crystallographic content of late nineteenth century kindergarten play a role in the explosion of research into the architecture of crystals? In other words, did the crystallographic content of kindergarten influence the future development of crystallography? Such an investigation would require a collection of early childhood biographies of the pioneers of X-ray crystallography.

It has often been observed that X-ray crystallography was unique in the physical sciences in the proportion of women among its greatest contributors. Kathleen Lonsdale, Dorothy Hodgkin, Rosalind Franklin, Helen Megaw, Caroline MacGillavry, and Isabella Karle are some of the early pioneers.[30] Why was this so? Is it possible that many girls were exposed to crystallography in kindergarten, *before* being systemically shut out of study of the natural sciences by conventional schooling biases? Information about the early schooling of Hodgkin[31] and Franklin[32] is available in recent biographies. Whether their curricula were influenced by Froebel is not apparent in these accounts.

Concluding Remarks

At home one evening, I was working at my desk on which laid a polarized light micrograph of extraordinary, pseudohexagonal, ferroelastic urea inclusion complex crystals[33] that were prepared by one of my favorite crystal engineers, Mark Hollingsworth. Dozens of incredibly sharp twin boundaries were vivid in a rainbow of interference colors. My kindergartner picked up the photo.

"Dad, are these crystals?"

"Yeah. My friend made them."

"Did he make them all by hisself [sic]?"

"Yup."

Thinking deeply. "I could make those all by myself!"

"Really?"

"You just cut out shiny, colorful triangles and tape them together."

"OK. Let's make some crystals." And off we went with paper, scissors, and tape to engineer ferroelastic crystals. Then, I was sure that Froebel was onto something. Rubin and Brosterman are surely onto something, too. This is evident in their recent publications that are sure to warm crystallographers with the conviction that what we do is not as insular as we might otherwise have thought.

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References

(1) In honor of Kurt Mislow on the occasion of his 80th birthday, and in gratitude to Stuart Sloan, Gary Tubbs, Tabitha Beaupain, Minka Andersen, Aden Kurth Kahr, and all the other inventors/explorers at the New School at South Shore, Seattle, WA.

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(3) While "kindergartner" is used in the English speaking world today to describe a kindergarten student, its usage in Froebel's Germany was as different as student is from teacher. For Froebel a "kindergartner" was, in Rubin's clarification, "the one who ploughed the soil of the child's natural curiosity, enriched it with materials conducive to self-activity, supplied the maps for its treasure hunts for answers, and pointed their little noses toward the sweet prize of discovery." Rubin, J. S. E-mail, March 21, 2003.

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