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# Self-Direction in Physics Graduate Education: David J. Rowe's Career-Long Commitment

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**Abstract:** The ability to self-direct a research program determines graduate degree completion. Yet, research on incompletion of graduate physics programs assume students' present level of self-direction adequate and neglects to recognize a lack of self-directed learning as key. One theoretical mathematical physicist focused on changing this challenge of physics graduate education by promoting self-directed learning through the type research flow that has been found to bring the greatest satisfaction to researchers with respect to their insights. This he provided through his space, time, open mindedness and theoretical contributions with his students and in collaboration with his colleagues. A self-directed learner himself, David J. Rowe developed methods of mentoring for encouraging physics graduate students to recognize symmetry as valuable in identifying solutions to problems quickly—helping these students take the lead in finding insightful resolutions to complex, multidimensional, mathematical physics uncertainties. How Rowe set about supporting self-directed learning in his graduate physics education interactions will be examined with the use of narrative research to interpret the texts and conversations with the author he made available. His techniques will be presented and recommendations made regarding how Rowe's work in this regard can be modeled to improve self-direction in STEM graduate education.

**Keywords:** self-directed learning; graduate education; flow; David J. Rowe; open mindedness; mentoring; symmetry; narrative research; STEM

## 1. Introduction

The ability to self-direct a research program determines completion of a graduate degree [1]. Nevertheless, instead of considering what is intellectually helpful for promoting the self-direction that leads to successful graduation, research on incompletion of graduate physics programs focuses on identifying what sociological factors are deemed necessary to change—primarily those to improve self-efficacy [2]—assuming the student's present level of self-direction adequate for success in academe [3]. Given that a lack of self-direction correlates to non-completion of the graduate program, the type of motivation physics graduate students have in approaching problem solving can have a profound influence on the developmental careers of those who would choose to be academic physicists [4].

Professor David J. Rowe (1936-2020), a theoretical nuclear physics with the University of Toronto for over 50 years [5] was one faculty member who focused on the type of motivation that was necessary to encourage graduate students to continue on in academe as physicists. A prolific researcher and graduate educator, Rowe considered success as a nuclear physicist to depend on physicists' ability to self-direct their learning to develop insightful work regarding nuclear physics.

How this would be accomplished in his estimation was primarily based on the application of symmetry to their problem solving in physics [6]. He promoted the value of symmetry in problem solving with his graduate students, his collaborations, and in his own work as a productive theoretical physicist [7].

The influential methods Rowe developed regarding symmetry in nuclear models will be presented with respect to the relationship they were seen to have to self-directed learning in graduate physics. It will be argued that his methods continue to be useful for success in identifying and solving self-determined STEM problems, aiding in completion of a graduate program. Suggestions will be made for how his methods can be advanced within the graduate student program to promote the success in academe that comes from self-directed learning.

### *1.1. Science, Symmetry and Nuclear Physics*

Arranged into theories and facts, science aims to organize and explain phenomena so that its results are reproducible, modifiable or falsifiable by independent observers [8]. This is accomplished through discoveries and inventions, where a discovery identifies the way that things work and inventions indicate how what we perceive can work differently, where sometimes the initial perception of the discovery is itself the invention [9]. Discoveries happen; in contrast, inventions demand that thought be given to whether this new means of perception is of value to those it is intended to serve [10].

As a fundamental aspect of the perception of phenomena [11], symmetry is one such devise that is both a discovery and an invention [12]. During the twentieth century, the development of quantum physics and relativity came with a semantic shift of the word “symmetry” in accordance with the increasing power of it as a conceptual instrument [13]. Symmetry, as a harmony of proportions [14], developed as fundamental to successful scientific prediction because without this invention all that is identifiable about facts is the binary opposition between “effect present/effect absent”. Numbers assigned to experimental results then act only as attributed names rather than fundamentally pointing to a method of ordering [15].

Why symmetries are necessary to understanding experience is a result of consciousness being a continuous and immediate in a continuity of time [16]. As such, without a method identifying individual aspects of consciousness and ordering them in some particular way there can be no thoughts about what is perceived and no information gleaned. Symmetry, as a space-time geometry [17], permits the identification of distinct objects to be considered and provides rules for how those objects are ordered in space-time.

The most important concept of symmetry is that space and time are isotropic and homogeneous, that is, all points and all directions in space are equivalent so that there is no real distinction of absolute location in time and space [18]. The symmetry of a system is an observed or intrinsic feature that remains unchanged (invariant) under some type of transformation [19]. It does so by specifying rules of operation, specifically in relation to one, two, three and four dimensions. Symmetry regarding each of these dimensions can be defined as invariant under these conditions: (1) a fixed one dimensional single point represents inversion [20] where the resulting symmetry has either positive or negative parity [21], (2) a fixed single point at one location of the object permitting variability at another location equivalent to $\frac{2\pi}{N}$ results in rotational symmetry [22], (3) symmetry in relation to a fixed two dimensional line promotes reflection [23], (4) variability with respect to a two dimensional line is translational symmetry [24], (5) transformational symmetries are those involving three dimensions [25], and (6) dynamical symmetry, symmetry in four dimension [26]. As that which reflects actual conditions most exactly, broken symmetry [27] is absolute once it was recognized that parity is not conserved in the beta decay of $^{60}$Co (Cobalt-60) [18].

Symmetries are divided into discrete—those with only two possibilities (e.g., reflection)—and continuous (rotational, for example) [28]. Restoring broken symmetry is accomplished by considering groups of objects where each relevant symmetry transformation is included as part of the group [29], giving a new perspective on static symmetry where an object is said to have static symmetry if it is invariant under a group of transformations [30]. As such, discrete symmetries are described by finite groups and continuous symmetries by Lie groups [28].

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With respect to the structure of nuclei, the processes that go on are dynamical regarding the energies of nuclear states, their spins and parities [31]. Experimentally revealed with $^{168}$Er (Erbium-168) as bands, the relationship of the bands in the energies of nuclear states was discovered to be an axially symmetric rotor [32] and the predictive power of the rotational model of interpretation of the band structure in nuclear structure has been enormously successful [33]. However, it does not reveal what goes on inside rotating nuclei; specifically, whether they rotate as solid objects or like fluids.

Early in his physics career, Rowe was able to demonstrate rigid-body flow with a microscopic rotational theory based on the highly successful adiabatic rotational model [34]. The flows for such a zero-viscosity fluid are irrotational flow, i.e., the currents do not circulate as the fluid rotates. Experiment provides results somewhere between rigid and irrotational flow types, suggesting a fluid flow with non-zero viscosity [35].

With respect to the dynamical group to explain the rotational motions, Rowe discovered that the set of irrotational flows is incomplete, exposing the impediment to constructing an irrotational-flow model while also indicating what to do about it [36]. Without the use of group theory and the concept of dynamical symmetry, it is unlikely this discovery could have been made [30].

Yet, the full dynamical group for collective motions must contain more than the transformations from one nuclear shape and orientation to another [37]. In addition, transformations giving the nucleus rotational angular momentum and vibrational momentum boosts must be contained. In other words, states of the nucleus in rotational and vibrational motion need to be generated [38]. This Rowe and his graduate student Rosensteel recognized as based on what is known in mathematics as the group of symplectic transformations denoted Sp (3,R) [39].

### *1.2. Self-Directed Learning*

Self-directed learning was important to Rowe. A psychological theory that regards the learning process as internally regulated [40,41], self-directed learning is based on what the learner personally values, relating to other learners as also self-directing their learning [42]. When this learning takes place in communities based on consensus decision making by finding a time and place to do what each learner values, the self-direction evolves from an individual approach to learning to a way of organizing social interactions when learning [43].

Self-directed learners are distinguished from other-directed learners by not being tied to a pre-determined schedule [44] and by demonstrating a lack of interest in learning purely for the purpose of gaining extrinsic rewards or praise from those in authority [45]. In contrast, these students learn because of an understanding gained from developing their unique perspective on the world. They determine when learning has been achieved at the level of expertise they have hoped because their learning is tied to what they intend to get out of the learning as it is they who evaluate their learning outcomes [46].

These learners most often prefer to learn from mentors of all ages [47]. They hold no stigma to learning from someone younger or less experienced than themselves as long as that person has something unique to provide that the learner values and desires or needs to understand for their learning to proceed. Similarly, self-directed learners may also search out elderly mentors if they are potentially informative regarding what the self-directed learner values [45] (see Figure 1).

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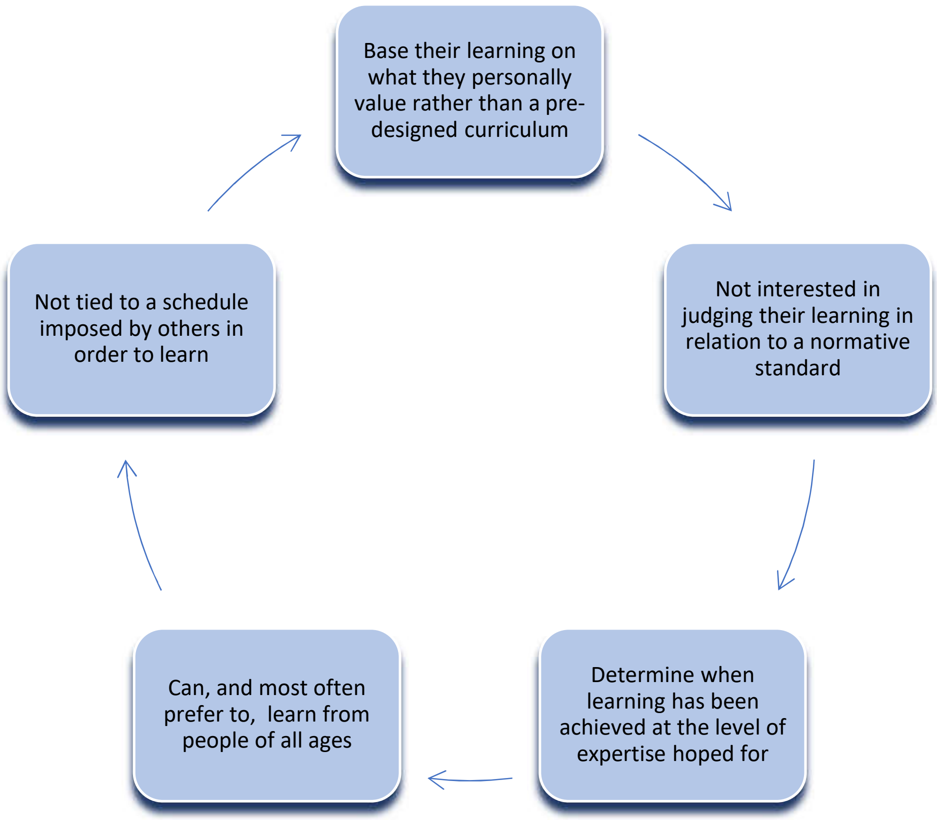


**Figure 1.** What distinguishes a self-directed learner?

To be self-directed learners, physics students are seen to require awareness of their (1) approaches to learning; (2) suitability for certain strategies for self-directed learning; and (3) satisfaction with self-directed learning [43]. A dissatisfaction with their ability to learn has been identified as being counterproductive in encouraging the positive attitudes and habits of independence required for self-direction in graduate students' learning [48]. Those graduate students who do participate in self-directed learning demonstrate high desire for both learning and self-direction, and in addition they also require self-management skills to be effective at self-direction [49].

Self-directed learning requires comprehension of what one values in learning and firmness of purpose to continue to investigate these values in times of boredom, indecision or conflict [50]. It also requires a similar acceptance of others as self-directed learners and acknowledging that the values of others, in providing unique points of view, are necessary to constructing a clear understanding of reality [51]. Together these various points of view are seen to provide our best estimation in constructing reality [52].

Self-directed learning has been recognized as the form of learning most appropriate for adults [53]. Yet, a reason that adult learning is seen to be self-directed may be that the research on self-directed learning has been conducted primarily on members of dominant cultures—white, middle-class. Others outside the dominant culture may feel they lack the ability to join the workforce without their post-secondary learning being other-directed by educators who are part of the dominant culture [54].

*1.3. Mentoring*

Encouraging self-direction in research, mentoring has been identified as unsurpassed in its ability to positively affect graduate students to increase their work satisfaction and fulfilment [55]. Mentoring can be defined as a deep, equitable learning experience with social transformative value [56]. With respect to the competitive research world, graduate students have an inferior position in the research hierarchy [57]. They are isolated in their work and require mentorship in various aspects of academe for successful program completion [58]. Graduate students' perceived experience with academic involvement strongly predicts their educational outcomes [59].

Different types of mentorship have been found valuable. These include opportunities for one-on-one conversations with faculty and cohort socialization activities identifying peer strengths and alliances [60]. Faculty mentorship is perceived by graduate students as important for initiation into the intellectual community where faculty mentorship and research engagement have been found to converge in graduate student success and be necessary for sustainable scholarship [61]. Peer mentorship has been recognized to have wide-ranging effects across four domains of graduate learning: academic, social, psychological, and career [62].

With respect to self-directed learning, mentorship has been found especially effective regarding the creation of student portfolios of their research when the portfolio is integrated into the educational routine and when they are designed to facilitate at least goal-setting, task-analysis, plan implementation, and self-evaluation [63].

For Rowe, mentoring was both the foundation to his own work as a self-directed learner and to the style of teaching that he considered most appropriate for supporting self-directed learning in his interactions with graduate students and colleagues.

### *1.4. History in Common of Self-Directed Learning Regarding David J. Rowe and the Author*

This author (Nash) first met Rowe in 1985 when he was Associate Dean, Physical Sciences at the School of Graduate Studies, University of Toronto and Nash was a graduate student representative in Education on the School of Graduate Studies Council. That year, they were members of a three-person committee to revise the election procedures for the School of Graduate Studies Council. From that time, it was evident to them that they both shared an interest in the role of self-directed learning in graduate education and as a research process.

As a philosopher of education, Nash was seen by Rowe to provide additional insight into his understanding of self-directed learning in advancing his mentoring relationship with his graduate students and research colleagues as well as enhancing his own research path as a mathematical physicist focusing on symmetry in nuclear physics.

In 1990, Rowe was awarded the Isaac Walton Killam Senior Research Fellowship. This fellowship provided Rowe with five years research support to work on *Fundamentals of Nuclear Models* with his long-time experimental physics colleague, John L. Wood. With part of the funds he received, he created a research assistantship for Nash (PhD 1989) to (1) help him encourage self-directed learning with his graduate students and colleagues, (2) support his own self-direction as a researcher by having Nash design a method using Adobe Illustrator for creating the numerous figures for the first chapter the book, and (3) to invite notable physicists to speak at the Department of Physics as Welsh Lecturers [64].

Rowe and Nash remained in contact throughout Rowe's life as close family friends. The last telephone conversation Nash had with Rowe was a few days before his death when he confirmed he had completed the final paragraph of his planned research program since the time he had developed his views on symmetry as the International Atomic Energy Agency (IAEA) Centre for Theoretical Physics, Trieste Visiting Lecturer from Oct.-Nov. 1966. In his own estimations, Rowe had accomplished all he had set out to do as a self-directed learner in mathematical physics by the time of his death, 8 May 2020. In all, Rowe and Nash were friends for thirty-five years. The following information is based in large part on their many years of discussions regarding self-directed learning.

### *1.5. Narrative Research*

The author assumes a distinct method to interpret the texts Rowe left and the years of conversations they had regarding self-directed learning. That method is narrative research. Narrative research is identified as one of the five methods of qualitative inquiry (phenomenological psychology, grounded theory, discourse analysis and intuitive inquiry representing the other four [65]). Defined as the varying perspectives of a story that can be constructed to make experience comprehensible [66] (p. 37), narrative research represents the treatment of data as stories [67] where narrative data result from a communication exchange [68] and an understanding of how human actions are related to the social context in which they occur [69].

It is the particular form of self-directed learning [70] Rowe supported that is attractive to a narrative researcher because it assumes self-directed learning, in addition to being an aim, is also a process to follow in achieving that aim. The process thus represents a story of self-direction accessible to a narrative researcher. It is for this reason that Rowe's method is one that is able bridge the interest of physicists—and STEM researchers concerned with self-directed learning in general—and that of narrative researchers.

## 2. Materials and Methods

How Rowe undertook to promote self-directed learning in his own research and in his supportive interactions with graduate students and colleagues was with respect to four aspects: his space, time, open mindedness and theoretical contributions. Each provided a necessary element to how Rowe promoted self-directed learning.

### *2.1. Space*

On the nuclear physics/high energy floor of the University of Toronto physics department, on the south side of the building, there were three rooms allotted to Rowe. Most westerly was his personal office, beside that to the east was a room for research associates and directly beside that in the southeast corner was a room for graduate students common to all nuclear physics faculty. The rooms were very different in character. The graduate student space was open, bright and divided into individual areas for each of the graduate students, of which there were about five at any time, two of whom were Rowe's. The next room, for research associates was a dark, utilitarian room that generally served only as a space for them to park their work or to work intently on their own. This lack of ambiance in the research associates' space was primarily because when post-doctoral fellows were part of the research program they spent most of their research time in collaboration with Rowe in his office next door.

Rowe's office was designed to offer the amenities of a faculty club. Important works in physics were visible in both a glass-fronted and two open dark oak bookcases. The three low, side-opening filing cabinets were also of dark oak while an additional dark oak occasional table on the opposite side from the filing cabinets hid another, smaller filing cabinet. The wall-to-wall carpeted room (considered a luxury in those days) held two dark oak arm chairs with upholstered seats on either side of the occasional table, while between these chairs and the window wall was Rowe's dark oak, modern-style desk. The desk created the space for his computer under one of the open bookshelves with his fridge for refreshments located between the computer and the window. On the window ledge was an impressively overgrown Euphorbia Trigona succulent plant. Each of these features of Rowe's office was designed to make Rowe and his collaborators feel as if they were meeting in a faculty club.

The most important aspect of the room's design was its central focus—the large whiteboard attached to the wall above the three, low, side-opening filing cabinets. It was on this whiteboard that the room was directed. Invariably, it would be covered with the ideas of Rowe and his colleagues for Rowe to ponder in between meetings and to initiate further discussion at the next meeting. It was the indispensable aid to Rowe's collaborative process.

### *2.2. Time*

Of utmost importance to Rowe was his particular view of research time. As a self-directed learner, Rowe was immersed in research time in the manner described as "flow": a desired time when the researcher's mind is stretched to its limits in a voluntary effort to accomplish something valued by them as difficult and worthwhile [71]. When Rowe was working, his mind was invariably in flow. Rowe felt extremely comfortable in flow as this was his natural experience of research. It may be for this reason that, similar to research findings on those who experience flow [72], Rowe's most positive experiences were those related to his research work.

Although Rowe did set up weekly meeting times with his colleague and his graduate students, the need for a specific time was very fluid and could change if Rowe or a colleague or student had a good idea to communicate. Then, Rowe would immediately drop what he was doing to hear the idea out—by phone, internet or in person in his office. Rowe would always invite students and colleagues into his office to have these discussions—among other reasons because it was in his office that he experienced the greatest incidence of flow in his thinking.

Rowe also was ever cognizant of time as something that was scarce and the time-consuming nature of solving physics research problems. He saw his contributions regarding symmetry as ways to decrease the time taken to arrive at profitable results and the ability to use symmetry as the key to taking the lead in finding solutions. It was because of this deep interest that he had searched for a way to make the value of group theory evident to graduate students, leading to the co-creation with Nash of a little monograph entitled *Symmetry, Art and Nuclear Physics*—published in house through the Department of Physics—that used photos of significant works of art to visualize different types of symmetry [73] and introduce his findings in relation to group theory.

### *2.3. Open Mindedness*

Rowe was not prejudiced regarding from whom he might learn. He believed 50% of physicists should be women, listened attentively to those of different disciplines who might shed light on symmetry, and seemed to have the wonder of a child when hearing of the ideas graduate students and colleagues might bring to a discussion. Although Rowe was internationally acclaimed as a theoretical nuclear physicist, he treated all those with whom he was engaged in a research conversation as an equal. The only criterion Rowe used to evaluate the research discussions he had with others was did they contribute to the discussion in an interesting way. If what was being imparted met this test then Rowe was open and receptive to learning from all others.

There were four men in particular who were influential in his growth as an open-minded self-directed learner. These included his friend from his undergraduate days at Cambridge, Howard, who taught him to think bravely and deeply on difficult matters; Sir Denys Wilkinson, a British nuclear physicist who encouraged Rowe while at Oxford to consider being a theoretical physicist rather than following through on his original plan to become an experimentalist [74]; Aage Bohr, co-recipient of the 1975 Nobel Prize "for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection" [75], who convinced him to come to work as a theoretical researcher at the University of Copenhagen after completing his PhD in 1962; and the physicist he admired most, Albert Einstein, whose method of using vivid thought experiments to imagine physical phenomena [76] was one that Rowe himself practiced in making his own contributions to symmetry using mathematical physics—a method he shared with his graduate students and associates.

### *2.4. Theoretical Contributions*

In Rowe's estimation, he never worked harder than from Oct.-Nov. 1966, when he created the series of lectures he delivered as the International Atomic Energy Agency (IAEA) Centre for Theoretical Physics, Trieste Visiting Lecturer. Although he hadn't undertaken this type of theoretical work before, yet, during that period when he had to deliver new lectures daily, he felt he wrote in a particularly inspired, clear and concise manner. Those lecture notes became, almost verbatim, his first book—*Nuclear Collective Motion: Models and Theory* [77]. This book outlined the research program he would undertake and work to complete until his death.

From the beginning, Rowe's aim was to use the book and the publications that followed to aid graduate students in self-directing their research in a number of different, yet connected, areas: Equations of Motion Formalism; Large Amplitude Collective

Motion, Coherent States, Classical & Quantum Mechanics; Microscopic Theory of Nuclear Collective Dynamics; Collective Models as Algebraic Models; Vector Coherent State Theory plus other Mathematical Physics; Shell Model and Coupling Schemes; and Quasi-Dynamical Symmetry and Phase Transitions [78]. Through the use of symmetry employed in each of these areas, Rowe believed that these topics were ones that were inviting and potentially fruitful for graduate students willing to make use of group theory.

Rowe's primary goal for his self-directed research program was, in his words, "the development of a microscopic theory of nuclear collective phenomena aimed at understanding nuclear collective dynamics in terms of interacting neutrons and protons" [78]. According to his stated research objectives [78], there were a number of breakthroughs in his research program resulting in publication—each gave graduate students and his colleagues improved theoretical foundations for their own independent research. The first advance was that the many-body theories of equilibrium states and elementary excitations could be expressed in an equations-of-motion formalism. The second success was the theory of large-amplitude collective motion initiated with a graduate student Rick Basserman reducing a complex many-body quantal system to a more conceptually accessible classical system.

This close relationship between classical and quantal mechanics was subsequently explored in collaboration with students and associates (Rosensteel, Ryman, Vassanji, Bartlett), constructing explicit maps from one to the other. In discussions, Rowe always credited his graduate student, George Rosensteel as the one who created the next breakthrough in the formulation of a microscopic theory of nuclear collective dynamics. Starting with a phenomenological model of observables and proceeding to an algebraic expression of the model in terms of a Lie algebra of observables, this strategy yielded a microscopic version of the Bohr-Motttelson collective model known as the symplectic or Sp(3,R) model. Using this model, major developments of this theory were made by Rowe's graduate students and associates (Rosensteel, Carvalho, Vassanji, Rochford and Bahri). Major developments continue to be made by Draayer and his students and colleagues at Louisiana State University using this model [78].

Continuing with his account of his research objectives [78], Rowe indicated that expressing the Bohr model as an algebraic collective model led to a particularly valuable result—a formulation of a Vector Coherent State (VCS) theory. Rowe's graduate students and colleagues (Le Blanc, Hecht, Repka, Turner) used VCS theory to construct representations of various Lie groups, Lie algebras and Lie superalgebras, along with the representations of algebraic models.

Former graduate students and colleagues examined the mathematical structure and applications of dual pairs of group representations intertwining the representations of dynamical groups of symmetry groups in various nuclear physics situations (Rosensteel, de Guise, Repka, Carvalho, Welsh). Furthermore, former graduate students (Turner, de Guise, Rosensteel) along with Rowe separately investigated the shell model coupling schemes associated with each symmetry type and then explored the result when the different symmetries are in competition. It was through these that Rochford, Repka, Bahri, and Rowe discovered the concept of quasi-dynamical symmetry—the mixing of different representations of a dynamical symmetry in a highly coherent manner creating the illusion of symmetry preservation [78].

The account Rowe provided of his research objectives and the graduate students and colleagues who worked in collaboration with him in accomplishing them was written by Rowe in 2009. For his research activities after that time, his long-time colleague, John Wood, has provided the articles that illuminate the final eleven years of Rowe's research career and those researchers associated with it.

Developments and applications of an algebraic version of Bohr's collective model were undertaken with Rowe in association with colleagues (Welsh, Caprio) [79]. Rowe considered a major goal of nuclear physics as determining the validity of the general form of the shell model as the standard of nuclear structure. He believed that new approaches were needed for deriving effective shell-model spaces. This work was undertaken along with colleagues Carvalho and Repka [80] to the extent that several advances extended the power and versatility of coherent state theory so that it became a vital tool in the representation theory of Lie groups and their Lie algebras. Capelli identities then became a focus of Rowe's research [81], most specifically concerning the construction of holomorphic representations of many Lie algebras by vector coherent state methods.

In the last five years of his research program, Rowe concentrated on improving the mathematical rigor of his work. This was done regarding dual pairs of holomorphic representations of many Lie algebras from a vector coherent state perspective along with mathematician Joe Repka [82] and with respect to microscopic evolution of the collective models and their underlying foundations along with McCoy and Caprio [83].

Rowe's collaboration with Wood was extended to examining isobaric analog states and nuclear shape coexistence [84] following on the publication of *The Fundamentals of Nuclear Models* [7]—summarizing the state of nuclear structure physics and the experimental and mathematical foundations for the models used to understand it a number of years before. The penultimate work of Rowe was a collaboration with Wood and Draayer's team in investigating the key role of the physics of nuclei as an emergent symmetry [85].

Rowe's final work was published one week before his death and was delivered to Rowe's hospital bed by Wood [86]. It was an article concerned with establishing a framework for exploring the dynamics of nuclear rotations [87].

## 3. Results

The results to be summarized will be those related to Rowe's support of self-directed learning in his graduate students and with his colleagues rather than the results of his theories he developed. As such, what will inform these results is the account published this year by his colleague at Louisiana State University (LSU), Jerry Draayer, regarding Rowe's role as a mentor.

According to Draayer, Rowe played a pivotal role in advancing an understanding of nuclear structure in such a way that these contributions act as an underpinning, paving the way for construction of a bridge to span the gulf between low-energy and high-energy nuclear physics [88].

Draayer considered Rowe one of the few first generation leaders in Fermion-based algebraic models. In his role as a graduate student mentor, four of Rowe's papers were recognized by Draayer as most pedagogically significant [89,30,90,91], spanning from 1985-2017.

With respect to the use of symmetry, Draayer identifies Rowe's theory as holding beauty, simplicity and ultimate utility. Commending Rowe as a "a gentleman scholar-scientist" [88], Draayer envisions the legacy Rowe left as a mentor to his graduate students and associates as a campaign to stimulate and engage them. In speaking of the effect that Rowe has had on his own research and graduate students, Draayer comments, "David Rowe was a master mentor and clever innovator—at LSU we are attempting to keep that spirit alive" [88].

An acknowledgement of the verisimilitude of this claim that Draayer's research group is keeping Rowe's spirit alive is the work that has been published by their team based on Rowe's theoretical structure since Rowe's death. Of the numerous publications associated with the research group at LSU indebted to the theoretical work of Rowe, a few of those papers focused on the symplectic model will be cited [92,93,94,95]. Rowe's legacy thus remains substantial as a mentor supporting self-directed learning specifically at LSU.

Rowe's most illustrious graduate student was George Rosensteel. It was Rosensteel who had the breakthrough idea in the formulation of a microscopic theory of nuclear collective dynamics in 1977 [39] that had such a fundamental effect on Rowe's research program. In his tribute to Rowe, Draayer refers to Rosensteel as a friend and major colleague, just an hour's drive away at Tulane University [88]. As such, it is relevant to consider in what way Rosensteel carried forward Rowe's legacy.

The last time Rosensteel referenced the work of Rowe in a publication was one in which Rowe was also a contributing author, published three months before Rowe's death. However, it was also the last time Rosensteel published any research. He himself died on 17 December 2021 at the age of 74 [96].

With respect to Rosensteel's influence on his own graduate students, Rosensteel's obituary noted the following, "He was kind and generous with his knowledge and his time. George brought out the best in people, challenged his students, and encouraged them to reach their potential [96]." In this generosity of time and knowledge, as well as his encouragement of graduate students to pursue what was within their potential, it can be claimed that Rosensteel had displayed the same values as his mentor, Rowe, with respect to graduate students and this particular attitude to research is now being carried on by the next generation of Tulane's physics graduate students.

## 4. Discussion

Self-directed learning has been cited as the optimal approach to research for a productive and influential academic career in physics [50]. Nevertheless, such self-directed learning is not easily undertaken by graduate students [49]. David Rowe was one physicist who was concerned about the need to encourage self-direction in graduate education and took measures to support and enhance it in graduate students, his associates and in himself. He did this in a variety of ways: providing an appropriate space for meeting to consider difficult problems in physics, being flexible with his time in listening to new ideas with an open mind, and by creating a number of innovations in group theory to promote self-directed learning in physics based on the ability of symmetry to provide a firm foundation for this self-direction in nuclear physics.

In self-directed learning, learners take responsibility for their own learning based on what they personally value. In self-directing, learners may have the ability to experience psychological flow in which the researcher becomes so immersed in the difficult, yet rewarding, work being undertaken that sense of time and place is lost. As such, flow and self-directed learning are not the same things. A researcher can be a self-directing learner and still be completely aware of time and place. Flow is not a requirement for the type of research that promotes success as a physics researcher. However, as has been reported by those who have experienced flow in their work, the experience of flow in working is that which is the most enjoyable [71].

For Rowe, the type of self-directed learning he wanted to support and felt most drawn towards was the experience of flow. Rowe spent much of his research time in the experience of flow. This was productive both for his own research work and his collaborations with graduate students and colleagues. However, given that when a person is in flow they are unaware of anything extraneous to the research problem representing their focus, the implication of this type of self-directed learning is it requires support to be continued for any length of time.

When Rowe initially began his career, his departmental administration came from various secretaries who supported his activities. However, later in his career, once each professor was expected to take care of their own correspondence and manuscript preparation through personal computers, Rowe easily took up using the computer and finding optimal ways to do so. However, in losing secretarial help, Rowe also lost filing support. As a result, surfaces in his office were covered in substantial mounds of paper waiting to be filed. This lack of easy access to his papers was a detriment to Rowe's research program as he often lost that which he most needed. This was why, among the other work Nash did with respect helping Rowe self-direct his research program, she also filed all the papers in his office, helping him to locate what he needed quickly.

Nash left as his research assistant when Rowe was sixty. At that point, he began to shift his operations from his departmental office to his home office. His concentration at this point increasing became his theoretical contributions for use by graduate students and colleagues rather than conducting regular, in-person meetings.

To increase flow in doing his research, he also started working during what he felt was his most productive period—from 4:30 a.m. until breakfast. Rowe was able to remain innovatively insightful in his work during the last part of his life with the dedicated help of his experimental physics collaborator, John L. Wood, and his wife, Una M. Rowe. Without their continuing, effective and sympathetic support of Rowe's need for flow as a self-directed learner, his ability to support graduate students and colleagues in their self-direction would not have been possible.

It is self-directed learning that is necessary to successfully undertake a research career in physics [97]. However, it is flow in conducting this research that brings the greatest happiness to researchers [98]. It was Rowe's aim to promote this type of happiness with graduate students and associates. Nevertheless, it was a result of the immense and appropriate support that he received by those who worked closely with him throughout his life that this type of flow was possible in his research.

Not all physics graduate students have access to such support to achieve flow [50]. Furthermore, this type of deep enjoyment of one's work is primarily an intrinsic motivator [99] rather than what researchers personally value of their work as expressed in their self-directed learning. Whether they achieved flow or not, from the legacy Rowe achieved with respect to his graduate students and colleagues, it is clear that his graduate students were able to maintain self-directed learning as a result of his mentorship.

The challenge of encouraging self-directed learning in graduate education is recognized in physics; however, it is ubiquitous to graduate education in science, technology, engineering, and mathematics (STEM) subjects. Recently, self-directed learning was cited as a "new trend" in STEM subjects that "students appreciate" [100]. That self-directed learning is only now being recognized as necessary for success in STEM subjects relates primarily to the new importance of virtual learning that requires independent initiative [101].

It should be reiterated that Rowe's method of mentoring for self-directed learning in physics is not the only way that self-direction in physics graduate students, and STEM graduate students in general, might be achieved [76]. However, what is unique about Rowe's method is that it was not only concerned with the achievement of self-directed learning but also assuming a particular process in conducting physics research that was entirely self-directed. It is this process that was the focus of this narrative research on Rowe's self-directed learning.

## 5. Conclusions

Rowe was a pioneer, both as a theoretical nuclear physicist and a proponent of self-directed learning, in recognizing the necessary value of self-directed learning for his graduate students and associates. For in-person meetings, Rowe devised a method of encouraging self-directed learning that focused on four aspects: space, time, open mindedness and theoretical contributions. This method produced a heritage of self-directed learning in his graduate students and associates. Regarding virtual meetings, Rowe focused on increasing the theoretical contributions he was able to provide to graduate students and colleagues both in his peer reviewed publications and his book cowritten with Wood, *Fundamentals of Nuclear Models*. These contributions in group theory can continue to encourage physics graduate students to take up self-direction and encourage researchers in other STEM subjects to incorporate similar methods in their areas of research.

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