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ABSTRACT
This article explores the history of the relations between computer science, information technology, and the art of dance. In the early years of computer choreography, scientists envisaged the development of visual displays and software tools to help in choreographic design. They used random number generators to create a variety of spatial displacements and body movements for the dancers—work that suggested that computer programs could be customized to suit the preferences of the individual choreographer. Such projections fell woefully short of what a large number of choreographers, computer scientists, digital artists, and professionals from different fields eventually achieved during the last half-century, not to mention what we might expect in the future. The convergence of dance creation and performance with advances in information science and technology constitutes a privileged ground on which to explore deep philosophical implications of our embodied mind.

KEYWORDS
Computer; information technology; choreography; dance; arts

Introduction

Interactions between science, art, and the humanities have been a subject of concern for intellectuals for a long time. From Plato's admonition to banish poets from his ideal Republic to C. P. Snow's portrayal of two cultures of literary intellectuals and scientists at odds with each other, the problematic relations between reason and emotion, thinking and feeling, in the conduct of human affairs have been debated by scientists and artists.[1]

At the dawn of computer science in the early 1840s, Ada Augusta, Countess of Lovelace and Charles Babbage's disciple and collaborator, anticipated the impact of information technologies on artistic endeavors, already arguing that Babbage's Analytical Engine "weaves *algebraic patterns* just as the Jacquard loom weaves flowers and leaves" (her emphasis). Furthermore, she went beyond simile to imagine a prophetic alliance between technology and music: "Supposing … that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ldnc.

compose elaborate and scientific pieces of music of any degree of complexity or extent."[2]

It would take more than a century before Ada of Lovelace's speculations would materialize. Advances in physics made it possible to construct updated and powerful versions of Babbage's Analytical Engine; as a result, in the early decades of the twenty-first century even the wider public agrees that technological advances in information and communications technologies can stimulate creativity and provide artists with new means of expression. The development of semiconductors and transistors in the 1950s, together with the electronic devices and software tools they led to, have revolutionized human activities. In particular, since the mid-1960s, computer scientists and dancers have teamed up to use advances in computer science, electronics, and information technology to organize, record, teach, and perform dance; to supply templates for choreographic design; and to improve the understanding of dance movements.[3]

The term "computer choreography" generally refers to the use of digital and analogic electronic means to assist in the creation and performance of dance. Originally focused on facilitating and enhancing the tasks of choreographers, the field expanded, as new tools became available, to include motion capture, storage, and retrieval; the design of spatial displacements and body movements; the control of lighting and music effects during performance; the provision of real-time feedback to dancers; and the use of algorithms, neural networks, and artificial intelligence to enrich the creative efforts of choreographers.*

The richness of human movements challenges attempts to unambiguously register, store, retrieve, display, and reproduce them. This is particularly the case for choreography and dance performance, in which complex permutations of body displacements, movements, and gestures combine with new technology-enabled music, lighting, and stage effects to provide aesthetic experiences to audiences. The main thesis of this review essay is that *computer choreography constitutes a privileged field for the exploration of fruitful and empowering interactions between scientific and technological advances on the one hand, and artistic endeavors and creativity on the other.*

Progress in semiconductors, movement sensors, sound and visual recording, computer architecture, coding languages, software programs, algorithmic procedures, machine learning, and artificial intelligence have opened new possibilities for choreographers and dancers, leveraging human creativity and providing new means for artistic expression, as well as new challenges for scientists and engineers. At the same time, tensions between the

* An algorithm is a set of rules or procedures to follow step-by-step to solve a problem or perform an operation, particularly in mathematics and computer science.

uncritical acceptance and instinctive rejection of technological advances in choreography and dance performance have motivated reflections on the ephemeral character of human actions and the nature of creative processes.

Projections of future developments made half a century ago, at the early stages of computer choreography, failed to capture the rich and diverse achievements that characterize the current situation in this field. The convergent efforts of scientists, engineers, choreographers, and dancers have transformed the ways in which dance is created, registered, retrieved, and performed. Yet, even more fundamental changes can be expected in the coming decades, particularly because the recent emergence of cyberspace and virtual reality—a new domain for the exercise of human faculties—opens up extraordinary possibilities.

The use of computers in choreography

Early reactions to the use of advanced information technologies in the arts and humanities ranged from technophobia to technophilia, with a tilt toward the former. This ambivalence pervaded the field of computer choreography for decades—a canvas painted with skepticism tinged with hopeful hues. Both instructive and cautionary tale, the history of computer choreography since the late 1960s registers attempts to strike a balance between defensive rejection and uncritical adoption of technology in the arts.

According to dance educator Judith Gray, "Many of us in the dance profession shy away from all things mechanical and electronic. 'Dancing,' we say 'is human. Machines are inhuman."[4] To choreographer Peggy Brightman, "Artists tend to be technophobic and computer illiterate."[5] Yet, such opposition deterred neither Gray from advocating that the profession enter the information age and take advantage of "increased opportunities for creativity and finesse" nor Brightman from requesting that computer scientists design programs that "all artists can use, which are affordable, portable, and which help in stimulating creativity in the dance-making process."[6] While technophobia has virtually disappeared among youth born into the digital age, technophilia still runs rampant among artificial intelligence enthusiasts, transhumanists, and singularity point believers for whom computers will soon be able to outpace human intelligence.[7]

Explorations of how artistic imagination could be leveraged by information technology have a rich history. John Pierce, director of the communications sciences division at Bell Labs, reported on experiments carried out in the mid-1950s using computers to compose, reaching the conclusion that they could "take over many musical chores which only human beings had been able to do before. A composer, and especially an unskilled composer, might well rely on a computer for much routine musical drudgery."[8]

About the same time French professor Abraham Moles, exploring the relation between information theory and aesthetic perception, suggested that "the first step of scientific aesthetics" was to structure the relationships among the parameters of the particular medium or combination of media that communicated the message. He offered a conceptual framework for analyzing ballet dance that included a psychophysical repertory of sound elements, elementary gestures and movements, positions, muscular mechanics, physiological possibilities, breathing, laws of effort, and rhythmic themes. While it is unclear whether Moles's conceptual scheme was ever used in practice, in the foreword to the English translation of the book, he mentions Michael Noll's experiments with computer choreography at Bell Labs.[9]

An early survey of computer applications in dance identified five areas in which they could be useful: notation systems for the recording of dance movements; animation and interpretation of dance notation; education and training of dancers and choreographers; choreographic composition and dance design; and analysis of dances.[10] A later report divided the uses of electronic tools in the performing arts into two categories: those whose effects featured as "an explicit part of the performance" and those that figured in the creation, design, or construction of the work. Among the first were video and audio recording and playback, possibly controlled by interactions with the dancers using wireless motion-tracking sensors. Among the second were software packages for virtual lighting design, audio processing, and choreography composition.[11]

Technophobic resistance to the potential contribution of computers to the creative capacity of choreographers has emerged recurrently since the 1960s. Dr. Noll, a pioneer in the field of computer choreography, wrote in one of the first academic articles on the subject, "Computers may play an important role in linking art and science, with the artist and scientist mutually assisting each other"; nonetheless, he cautioned, both artists and scientists had demonstrated emotional reactions and prejudices against the very concept of computer art.[*]

Brightman clearly stated the resistance in 1990: "Dancers, perhaps more than other artists, are tradition-bound, and confined by the boundaries of their own personal experience. Perhaps the computer offers a new and exciting escape from this confinement."[12] Fifteen years later, Thomas Calvert and his colleagues—among the leading experts in the design of computer choreography programs—confirmed the reluctance of dance professionals to accept those potential contributions: "Of all the art forms,

[*] Michael Noll, "Computers and the Visual Arts," in *Design and Planning 2: Computers in Design and Communication*, ed. Martin Krampen and Peter Seitz (New York,: Hastings House, 1967), 65. A bibliography compiled twenty years ago listed close to one hundred articles and books, and the number has grown significantly since. See Michelle Nesbit Hill, "Dance and Technology Bibliography," UC Santa Cruz: Alumni, February 11, 1996, http://alumni.cse.ucsc.edu/~michelle/dance.html.

dance has probably been the slowest to adopt technology. In part, this reflects the reluctance of dancers and choreographers to let anything get between them and the live kinesthetic experience."[13]

Five decades of experiments enlisting the diverse expertise of computer scientists and choreographers provide a rich source of material for explorations of the way in which computer science, electronic devices, and information technology can enhance human creativity. Table 1 classifies the experiments reviewed in this essay, providing references to the authors who reported on them. Most of the initiatives fall into the first category of using information technology and computers to record, preserve, teach, and perform choreographic works, and in designing and performing choreography. A second batch of experiments emerged after technological developments in video, motion sensors, and related devices that allowed the capture and processing of motion, and provision of feedback to dancers as they performed and interacted onstage with computer-controlled elements such as light, sound, and physical object. A third group of experiments involves the use of scientific and technological metaphors to inspire choreographic design, and in turn the harnessing of dance performance to stimulate philosophical reflections on the ephemeral character of human endeavors and the nature of consciousness. A final category—still not fully realized but clearly in sight as a result of advances in artificial intelligence and virtual reality—envisages the application of information technology: mediated, real-time audience participation in choreographic creation and performance.[14]

This article examines chronologically and thematically key developments in the field of computer choreography since the late 1960s. Following the structure of Table 1 and interspersing quotations from the main protagonists, it first describes, against the backdrop of early attempts at using computers to assist choreographers, an experiment from the late 1960s in which I was directly involved. Our goal was to write a program for and to implement the performance of a computer-generated dance onstage. The essay then focuses on attempts to create computer-aided systems to record, preserve, analyze, and teach choreography. Aspirations and hopes at this early stage exhibited a curious mixture of restraint and ambition, but utterly failed to anticipate how, after a slow, thirty-year gearing-up period, applications of information technology in dance and choreography would vastly outstrip whatever we managed to imagine in the 1960s.

The next section focuses on development during the last three decades of the twentieth century, contrasting expectations with realizations and exploring how, as technology advanced and choreographers became more proficient in using it, experiments distinguished between what made sense in computer choreography and what did not. Finally, I examine what

Table 1. Fifty years of interactions between information technologies and choreography.

Types of interactions			Period and authors (date of publication or of experiment)		
			Early stages	Late twentieth century	Early twenty-first century
1. Use of computers and information technology in the process of creating and performing choreography	1.1 Record, preserve, recall, analyze and teach dances and choreography	1.1.1 Use, adapt, or create dance notation systems to represent graphically and visually and to preserve choreographic designs	Noll (1967); Cunningham, as reported by Noll (1994, 2016)	Calvert (1986); Gray (1988); Venable (1989); Brightman (1990)	Wilke et al. (2005); Ebenreuter (2008); de Boer (2017)
		1.1.2 Use video recording and motion sensors to preserve and analyze dance movements with the help of computers		Simon Frazer University, University of Iowa, University of Waterloo, University of Pennsylvania, as reported in Politis (1987)	Zillner et al. (2002); Brick and Boker (2011); Salazar Sutil (2012); Aristidou et al. (2015); Jadhav et al. (2015); Crnkovic and Crnkovic (2016); de Boer (2017)
		1.2.3 Teach and train dancers, choreographers, and robots, using computerized dance recordings, visual displays, and algorithms		Politis (1987)	Gwee (2012); Jadhav et al. (2015); Abe et al. (2017); McGregor and deLahunta (2008)
	1.2 Assist and enhance the choreographic design process indirectly offstage: use computer programming languages, genetic algorithms, and artificial programs to explore options and decide on movements to design choreography in advance of performance		Pierce (1965); Beaman (1965); Noll (1967); Hutchinson, reported in Reichardt (1968); Moles (1968); Sagasti and Page (1970)	Herbison-Evans and Politis (1988); Landsown (1978, 1996); Ungvary et al. (1992); Bradford and Côté-Laurence (1995); De Sola, as reported by Katz (1998); Mebius (1998); Ventura and Bisig (2016)	Zillner et al. (2002); Klein et al. (2002); Hsieh and Luciani (2005); Lapointe (2005); Downie (2005); deLahunta (2008); Forsythe (2009); Carlson *et at* (2011); Gwee (2013); Jadhav et al. (2015); Ventura

(*continued*)

Table 1. Continued.

Types of interactions			Period and authors (date of publication or of experiment)		
			Early stages	Late twentieth century	Early twenty-first century
					and Bisig (2016); Crnkovic-Friis and Crnkovic-Friis (2016); Du et al. (2017); McGregor (2017)
	1.3 Complement or substitute for the choreographer	1.3.1 Complement the choreographer's work with dance segments generated by the computer and integrated into a single choreography (may include computer-designed imagery and virtual dancers)			Lapointe and Époque (2005); Downie (2005); Gwee (2012)
		1.3.2 Substitute for the choreographer using generative algorithms and artificial intelligence to produce machine-designed dances without, or with very limited, human intervention			Gough (2005); Donahue et al. (2017)

(*continued*)

Table 1. Continued.

Types of interactions		Period and authors (date of publication or of experiment)		
		Early stages	Late twentieth century	Early twenty-first century
2. Use IT to design and control lighting, sound, or mechanical devices interacting with performing dancers	2.1 Directly onstage: Use video or sensors on dancers' bodies to capture, process, and project real-time movement onstage, either directly or as mediated by a human dance jockey who gives onstage instructions to the performers, TV camera operators, musicians, etc., by modulating computer-generated dance movements in real time.		Cordeiro (1977); Stopiello and Coniglio (2002)	Cordeiro (2007); Schiphorst (2007); Sicchio (2014); Isbister et al. (2016)
	2.2 Indirectly, offstage: in advance, design lighting, sound, and virtual dancers to accompany, complement, enhance, and interact with performing dancers			Choreographic Coding Labs (2009); Mondot and Bardienne (2017); McGregor (2017)
3. Use computer, physical, and biological sciences as metaphors to create choreography, and use choreography as a stimulus for philosophical speculation	3.1 Use scientific concepts to inspire choreographic designs			Streb, Armitage, Miller, and Rothlein as reported in Morgenroth (2010); Salazar Sutil (2012); Ventura and Bisig (2016)
	3.2 Use the interaction between IT and choreography as an entry point for examining consciousness and ephemerality			Bleeker (2017); Noë (2017)
4. Use information technology–mediated, real-time audience participation in the creation and performance of choreographies and dances				Bleeker (2017)

Prepared by the author. Please note that some of the sources are placed in more than one cell, especially during the early twenty-first-century period, because they illustrate more than one type of interaction between computers and choreography. References can be found in the endnotes.

happened during the first decade and a half of the twenty-first century, when advances in electronic devices, computer architecture, machine learning, and artificial intelligence began to show their prowess and versatility in digitalizing and affecting practically every aspect of our lives. This expanded considerably the possibilities for choreographers wishing to use information technology, and led to an explosion of inventiveness that began to realize the full potential of computer choreography.

The essay concludes with a selective review of the 2018 computer choreography scene, a brief account of the resurgence of technophilic viewpoints, and speculations about future interactions between computer science, information technology, and the arts.

The beginnings of computer choreography in the 1960s

The first attempts at using computers in choreography date from 1964, when dancer Jeanne Beaman, in collaboration with computer scientist Paul LeVasseur, devised a computer program to create dance sequences for an individual dancer, using a random number generator to define tempo, movement, and directions.[15] Two years later, in collaboration with Dale Isner, Beaman did the same for groups of dancers. Their program-generated commands that led to choreographies with graphic titles, such as *Stationary Dance*, in which the computer defined the initial location for each dancer who remained in place until the end. *Cluster at the Center, Once Off Stay Off,* and *Circling Counter-Clockwise* similarly described the displacement of the dancers. Yet, the question of how to relate the movements to one another, or whether instead to emphasize the dancers' separateness, remains an area of decision for the dancer—not for the machine. Choreographer and dance notation scholar Ann Hutchinson tried the same approach in England shortly thereafter.[16]

In 1967, Noll suggested that the arts could benefit from applying techniques "to generate visual displays of scientific data" recently developed in computer science.[17] He further described how this could be done in the field of dance:

> One can assume that the choreographer has a digital computer with some form of real-time visual display at his disposal. Instead of using the ballet corps as his choreographic instrument, the choreographer could interact with the computer during the creative process. Stick figure representations of the dancers could appear in some form of three-dimensional display on the face of an electronic display tube. The choreographer, by manipulating different buttons on the console, could control the movement and progress of the ballet. Different dance movements might be stored in the computer's memory and put together at will. Individual movement restrictions could even be introduced into the process.[18]

Noll proceeded to describe his own experiment: "I incorporated random motion around a stage employing six stick figures: three large 'male' figures and three small 'female' figures.… I envisioned a creative choreographic situation in which the choreographer would interact in real time with a computer to compose a ballet while manipulating and seeing computer-generated stick figures."[19]

The movies resulting from these programs were shown to various choreographers, and it appears that Merce Cunningham, who would later use these techniques in his work, was aware of these experiments.[20] However, as Dr. Noll indicated at that time, despite much interest, the technology of user-friendly visual computer interfaces was not then available. Reflecting on his 1960s work fifty years later, he said, "I believed that in the computer, the artist had a new artistic partner."[21] At the same time, one should consider an important qualification he introduced twenty years earlier: "The computer is only a medium, and the medium should not be emphasized over the artistic results."[22]

An early experiment on the interaction between dance and computers*

Without knowledge of the work of Noll, Beaman, or LeVasseur, in the fall of 1967 I was involved in one of the first attempts to create and stage a computer-generated choreography for multiple dancers. Working together with fellow student Willam Page, with the support of Professor Robert Reifsneider of the Department of Theatre Arts at Penn State University, and with the participation of theater arts students, we devised a computer choreography program to generate dance sequences for a work of choreography to be performed onstage in March 1968.

Our objective was to show that computers could help to devise dances more effectively, but that no matter how sophisticated a computer program could become, it would never replace the choreographer. The idea was to allay the fears of technophobic artists who viewed technology with suspicion and to cool the enthusiasm of technophilic computer scientists who believed that artistic process might be simulated with a more complicated kind of program. As graduate students in our early twenties, we intuited a potential middle ground—a domain of compatibility between computer scientists and choreographers.

Designing the computer program

Aware of the notational difficulties in specifying the movements of dancers, and facing money, time, and staging-feasibility constraints, we decided to

* This section is summarized from Francisco Sagasti and William Page, "Computer Choreography: An Experiment on the Interaction between Dance and the Computer," *Computer Studies in the Humanities and Verbal Behavior* 3 (January 1970): 46–49. This short-lived academic journal, printed by Mouton & Co. in The Hague, saw the publication of five volumes between 1968 and 1974.

program just the displacements of dancers onstage, leaving decisions on individual movements and motivations to the choreographer and the dancers. The computer program specified the number of dancers onstage at the start of the performance and in successive time frames, where each should enter or exit the stage, and their displacements on the dance floor. The stage was divided into a network of thirteen regular hexagons marked on the floor,* and at any moment in time the computer program assigned each dancer to one of these hexagons, subject to a set of rules.

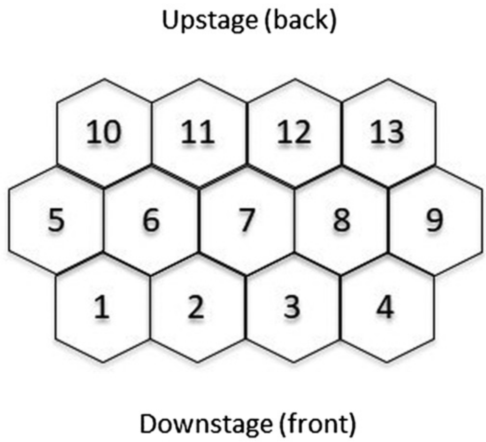
We built the following rules into the initial program: (1) in each transition a dancer could remain in the same hexagon or move only to an adjacent one—which prevented dancers from jumping from one end of the stage to the other in a single leap; (2) dancers could leave or enter the stage only from the hexagons closest to the side of the stage; (3) the program would handle a maximum of twelve dancers; and (4) the program would define the positions of all the dancers on the stage for any number of musical measures or independent time segments.

Using a random number generator and these rules, the program chose a number between one and thirteen to represent a dancer's position on the stage; it then compared that position with the previous one and, if the transition complied with the rules, the displacement of the dancer was decided; if not, a new random number was generated until a hexagon that satisfied the restrictions was selected.† The procedure was essentially the same for a dancer entering, exiting, or moving onstage. A modification introduced later allowed a dancer to remain in the same hexagon for between three and ten measures, with the length of his or her stay also determined at random. We set no restriction on the number of dancers that might be assigned to the same hexagon at the same time, and in this way the computer program generated groups of dancers. A set of computer printouts showed the position of each dancer, with one column for the time measure and another for the number of the assigned hexagon (Figure 1).

The program consisted of a master set of instructions (routine) for the computer that, as required, called on several lower-level packages of commands (subroutines) to perform specific tasks: fix the number of dancers onstage, indicate where a dancer should enter or leave the stage, define the sequence of displacements for each dancer, set the time each dancer would remain in a particular hexagon, and so on. We used the programming language FORTRAN IV in an IBM 360/65 with 1 MB of memory, which had

* Regular hexagons were used because movements from the center of one hexagon to the center of any adjacent one involves the same travel distance, which does not happen with a network made of squares or rectangles.

† The process of selecting the position onstage of each dancer is analogous to a first-order Markov process, meaning that the position of a dancer at any moment in time depends only on the immediately preceding one.



Dancer No 3

TIME	POSIT	TIME	POSIT
1	6	8	7
2	6	9	2
3	6	10	2
4	7	11	2
5	7	12	2
6	7	.	.
7	7	.	.

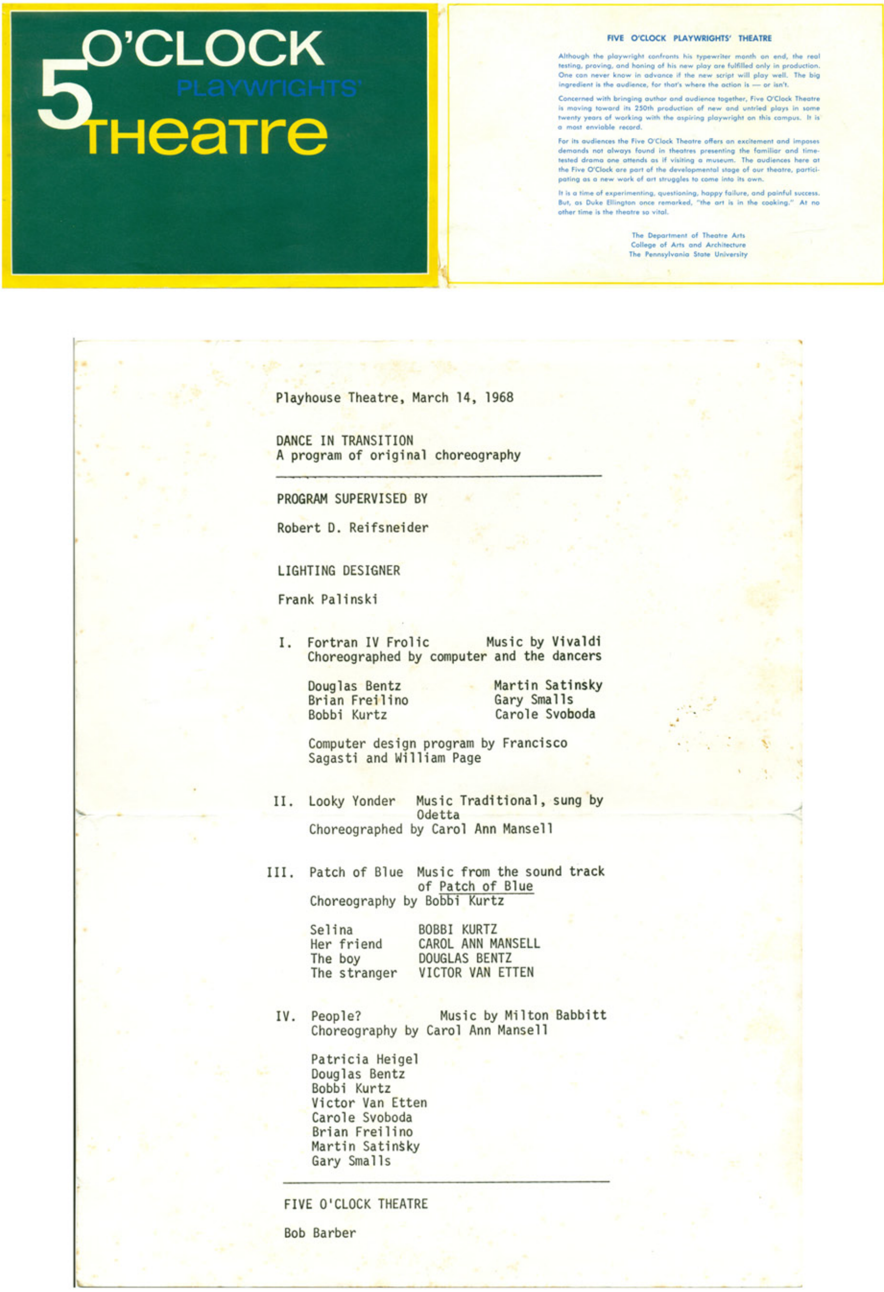
Figure 1. Partition of the stage floor and example of score for one dancer in Francisco Sagasti–William Page computer-generated choreography performed at Pennsylvania State University in 1967. Dancers can only enter or leave the stage through hexagons 1, 5, and 10 at stage right and 4, 9, and 13 at stage left. Dancers in one hexagon can move only to the adjacent ones in one step. For example, a dancer in hexagon 7 can only move to the hexagons 2, 3, 8, 12, 11, and 6, before proceeding elsewhere.

been installed at the Penn State Computer Lab less than a year earlier. For the stage performance we set the computer choreography program for six dancers, and our program had to be run after midnight, when the computer had no other tasks to carry out.

Staging the computer-generated dance

At the time the computer program was being written, the Department of Theatre Arts of Pennsylvania State University was organizing one of the "Five O'clock Playwrights' Theatre" series of student workshops under the direction of Professor Reifsneider. After several weeks of rehearsal, the computer-generated dance was put onstage on March 14, 1968 (Figure 2). While the computer program generated instructions for displacements onstage, decisions regarding individual movements were left to the dancers and the choreographer. Professor Reifsneider supervised the staging process and chose a movement from a Vivaldi violin concerto comprising 107 measures in 4/4 meter, with a metronome marking of 60 or one second to the beat. Hence, we set the computer program to determine the position of the dancers onstage at 107 different moments in time, following the rules already described. We repeated the sequence of measures twice to create a dance that lasted about five minutes.

The student dancers received with curiosity and enthusiasm the idea of performing computer-designed choreography; most of them had only a dim idea of what a computer could do and required several explanations of the



FIVE O'CLOCK PLAYWRIGHTS' THEATRE

Although the playwright confronts his typewriter month on end, the real testing, proving, and honing of his new play are fulfilled only in production. One can never know in advance if the new script will play well. The big ingredient is the audience, for that's where the action is — or isn't.

Concerned with bringing author and audience together, Five O'Clock Theatre is moving toward its 250th production of new and untried plays in some twenty years of working with the aspiring playwright on this campus. It is a most enviable record.

For its audiences the Five O'Clock Theatre offers an excitement and imposes demands not always found in theatres presenting the familiar and time-tested drama one attends as if visiting a museum. The audiences here at the Five O'Clock are part of the developmental stage of our theatre, participating as a new work of art struggles to come into its own.

It is a time of experimenting, questioning, happy failure, and painful success. But, as Duke Ellington once remarked, "the art is in the cooking." At no other time is the theatre so vital.

The Department of Theatre Arts
College of Arts and Architecture
The Pennsylvania State University

Playhouse Theatre, March 14, 1968

DANCE IN TRANSITION
A program of original choreography

PROGRAM SUPERVISED BY

Robert D. Reifsneider

LIGHTING DESIGNER

Frank Palinski

I. Fortran IV Frolic — Music by Vivaldi
Choreographed by computer and the dancers

Douglas Bentz — Martin Satinsky
Brian Freilino — Gary Smalls
Bobbi Kurtz — Carole Svoboda

Computer design program by Francisco Sagasti and William Page

II. Looky Yonder — Music Traditional, sung by Odetta
Choreographed by Carol Ann Mansell

III. Patch of Blue — Music from the sound track of Patch of Blue
Choreography by Bobbi Kurtz

Selina	BOBBI KURTZ
Her friend	CAROL ANN MANSELL
The boy	DOUGLAS BENTZ
The stranger	VICTOR VAN ETTEN

IV. People? — Music by Milton Babbitt
Choreography by Carol Ann Mansell

Patricia Heigel
Douglas Bentz
Bobbi Kurtz
Victor Van Etten
Carole Svoboda
Brian Freilino
Martin Satinsky
Gary Smalls

FIVE O'CLOCK THEATRE

Bob Barber

Figure 2. Program of the performance that included the computer-generated dance (*Fortran IV Frolic*).

program and how we envisioned mapping out the dance onstage. They immediately associated the idea of computer choreography with rigid and jerky mechanical gestures and had difficulty understanding the concept that, while they were free to select their own movements, they must abide by the series of displacements in spatial location determined by the computer.

We distributed printouts of the sequence of stage positions for each measure to the three male and three female dancers. As it turned out, the first set of printouts was generated by a version of the program that did not allow any dancer to stay for more than one measure in any one hexagon on the dance floor. The result was onstage pandemonium. Each dancer was too busy moving from one location to another to meaningfully interact with the other dancers. It was then that we decided to modify the computer program to allow each dancer to remain in the same hexagon for a period lasting from three to ten measures.

We generated a new set of printouts using the revised program, asked the dancers to memorize their sequence of displacements, and ran the dance again, first without music and then with it. The dance that resulted had an aesthetic quality, but as long as all decisions about movement and style were left to the individual dancers, a general sense of disorder prevailed. Professor Reifsneider intervened, deciding that the general mood of the dance would be slow, ceremonial, and mannered and that at several moments some or all of the dancers would perform the same individual movements to maintain the overall harmony of the dance.

Within these restrictions and those imposed by the computer-generated printouts, dancers had ample opportunity to exercise ingenuity in selecting and interpreting their body movements. As a group, they decided to turn the dance into a humorous love satire. In one of the sequences of displacements, a male dancer kept on following a female dancer from one hexagon to another, while she tried to escape by immediately moving to an adjacent one; frustrated, he turned his attentions to another male dancer who happened to move for a few measures in the same hexagon as he. What resulted was a curious mixture of computer-generated spatial displacements and slow, gestural movement—which the dancers used to relate to one another—performed to the accompaniment of baroque music. The dancers' humorous interpretation of the dance's meaning produced an amusing performance that the audience enjoyed (Figure 3).

We observed with interest the reactions of the performers during rehearsals. The sequence of displacements placed two dancers onstage at the start of the dance; after a few measures it dictated that the remaining four enter; but the fifteenth measure disposed of one of the dancers, who never returned again. The dancers could not believe the computer had made these decisions by generating random numbers and thought that William Page and I had instructed the computer to do so. The idea of a computer "deciding on its own" was alien to their minds, and the dancer who left the stage on measure 15 felt mildly bitter about it.

Figure 3. Photographs of the March 14, 1968, performance of *Fortran IV Frolic*.

Some implications of the computer choreography experiment

This early attempt at combining computer-generated displacements, general directions from a choreographer, and dancer responses to what was in essence a "spatial score" revealed the benefits of engaging in a collaborative creative process: randomly generated sequences could offer a vastly enlarged spectrum of choreographic ideas.* The capacity to generate a huge number of sequences augmented what the choreographer could imagine, but he or she could also accept or discard these sequences of spatial displacement according to his or her aesthetic preferences, instructing the computer to store the preferred ones. Essentially, the collaborative team could create a database to define criteria for accepting or rejecting future randomly generated sequences. If this process were extended to other movement parameters, such as facing (upstage, downstage, stage right, etc.) or level (standing, kneeling, sitting, or lying down), through an iterative process, the choreographer could "teach" the computer to generate

* The idea of using a random number generator to introduce variety and surprise in human activities had been proposed by computer science pioneer Alan Turing in 1951: "There is, however, one feature that I would like to suggest should be incorporated in the machines, and that is a 'random element'. . . . This would result in the behaviour of the machine not being by any means completely determined by the experiences to which it was subjected, and would have some valuable uses when one was experimenting with it." Alan Turing, "'Intelligent Machinery, a Heretical Theory.' Lecture given to '51 Society at Manchester. c. 1951," The Turing Digital Archive, 130, accessed May 28, 2018, http://www.turingarchive.org/browse.php/B/20.

displacements and body movements according to his or her creative preferences or style.*

The authors of the computer program envisaged a combination of software tools and hardware equipment that could be placed at the service of the choreographer. Over the following three decades, this happened in fits and starts, though it did not become the widespread phenomenon we anticipated. Yet, neither did we imagine the multiplicity of ways in which computers and other information technology devices would be used after powerful and inexpensive microchips became available at the turn of the century, nor how they would empower both choreographers and dancers. Our focus on the skeptical reactions of the dancers in *Fortran IV Frolic,* together with the limited capacities of hardware and software at our disposal, restricted our views of the future to rather simple extensions of what we had devised and put onstage.

Little did we anticipate that, half a century later, body sensors, video recording and projection, sound amplification and distortion, interactive lighting schemes, algorithms and artificial intelligence tools—not to mention the mapping of a choreographer's DNA as a generator of an immense number of possible dance sequences that continuously change from one performance to another—would push the boundaries of what "computer choreography" was all about.

Dance recording, reproduction, and notation systems

The conceptual innovations, technical advances, and experimental performances at the beginning of computer choreography in the 1960s paved the way for subsequent efforts during the rest of the century. Yet, hurdles remained, stymieing attempts to marshal the full potential of the new tools of information technology. One of the first problems encountered by those attempting to link computers and choreography was how to represent human movements using digital programming languages so as to faithfully record and retrieve dance sequences.

In the late 1920s, Austro-Hungarian architect, dancer, and choreographer Rudolf von Laban developed "choreutics," a method to record and analyze human movement, which allows precise specification of dance, sport, theater and other types of bodily movement. The graphic notation system associated with Laban's theories, Labanotation, uses abstract symbols to

* Such a possibility was also envisaged by Alan Turing in his seminal Manchester address in 1951: "If the machine were able in some way to 'learn by experience' it would be much more impressive. If this were the case there seems to be no real reason why one should not start from a comparatively simple machine, and, by subjecting it to a suitable range of 'experience' transform it into one which was much more elaborate, and was able to deal with a far greater range of contingencies." Turing, "'Intelligent Machinery, a Heretical Theory,'" 257.

describe parts of the body, direction, time, duration, level, and type of effort involved in a sequence of movements. Labanotation's complexity derives from its objective of representing, with as much detail as possible, the enormous variety of possible human movements. This complexity made the system rather difficult for dance practitioners to employ in their daily activities.

"At this time, no comprehensive language for human movement exists," stated computer scientist Thomas W. Calvert in 1986; yet he would later become part of a team that developed the first commercial computer choreography program. He reviewed dance notation systems, including Labanotation, Benesh, and Eshkol-Wachman, which, in addition to recording dance movements, had also been used in industrial time and motion studies, ergonomic analysis of body movements, and documentation of behavioral patterns. Calvert sketched the theoretical principles involved and indicated that the language they devised evolved into a "multi-component system made up of a very sophisticated interface for user interaction, a set of hierarchically organized expert system and knowledge bases and a high-quality display for the output of animation."[23]

By the end of the 1980s, computer scientists recognized the challenge of using Labanotation, or any other movement notation system, to develop computer choreography. Noting the difficulty and lack of user-friendliness of notation systems for professional dancers, Brightman argued, "The 'shape' of the body in space is not a very useful way of coming up with a new dance movement.… [T]he choreographer's basic tasks—discovering, inventing, and/or transforming and combining new movement—have not yet been fully addressed."[24] This basic incongruence between the dancer's phenomenological-kinesthetic experience of movement and the theoretician-empiricist's methods of cataloguing it continues to bedevil interdisciplinary thinkers at the intersection of the two fields.

Despite numerous attempts to link movement notation systems to visual representations as aids to the choreographer, problems for users remained intractable because, according to Calvert, no "unique, unambiguous way" of encoding human movement existed. While humans could successfully transcribe the notation into a movement language, at least at a conceptual level, the notation by itself could not yield "an unambiguous machine-readable representation,"[25] for it encodes neither the contextual relations nor the inner states of being that confer meaning to movement.

Yet this did not deter the efforts of several research groups, some of which met with a modest degree of success. In some cases, researchers linked notation systems to video recording and body sensors to track a dancer's movements, which in turn connected to visual displays and software algorithms that translated recorded data into symbolic notation choreography scores.

LabanWriter, a specialized graphics editor for creating Labanotation scores—designed by dancer and Labanotation expert Lucy Venable—paved the way for other advances. By the mid-2000s researchers at Credo Interactive, Simon Fraser University, and the University of Waterloo succeeded in developing *LabanDancer* "to translate LabanWriter files into animation for a single figure."[26] A visual display provided a graphic interface, showing a figure of a dancer onstage on the right and the Labanotation score on the left. The user could drag the cursor to move forward or backward in the score.[27]

Beyond dance notation applications, researchers have explored Laban's theory of movement analysis while focusing on different techniques of graphic representation, video, and motion capture to conceptualize and design choreographies. Academic researcher and dance performer Nicolas Salazar Sutil argued, "Laban's graphic approach encourages the use of visual media and technologies… for the better understanding of movement… as a form of material thinking, and not only within the context of dance training, but also as part of a vision of the dance that is complete in its philosophical perspectives, and which Laban called choreosophy."[28]

Sutil explored this integrated approach in *Solid Sense*, a dance jointly created with a biologist and a mathematician, which built on the relations between a dancer's body, spatial shapes patterned after viruses, and digital media images.

Other innovations and experiments aimed to improve the recording, preservation, and retrieval of choreographic designs; to simplify and make visually accessible dance notation systems; to use video and body sensors to register accurately the body displacements of dancers; and even to teach robots how to imitate human movements. Box 1 describes some of these experiments.

Box 1: Dance Notation and the Tracking, Recording, and Visualizing of Movement
After reviewing several dance notation systems and noting their limitations and advantages, in 2008, graphics designer Natalie Ebenreuter concluded that Labanotation and animation technology could be combined "to record, edit, and visualize a wide range of human movement";[29] however, before the wider dance community would use such a tool, concerns about the accessibility of Labanotation had to be addressed.[30] This led Ebenreuter to design LabanAssist, a prototype application that facilitated novices as they learned Labanotation to compose their own scores and enabled them to express their creativity with greater specificity through "syntactic and grammatical precision."[31]

Using Laban Movement Analysis (LMA), Aristidou and colleagues developed an algorithm to compare and assess human motion, and to design a virtual reality simulator to teach folk dance. Body sensors and optical trackers captured the changing positions of the different parts of the skeletal structures of dancers, which the researchers then analyzed using a computer to describe the four LMA components—body, effort, shape, and space. They next recorded experienced performers in order to build a database of several Cypriot folk dances, and used a correlation motion analysis algorithm to assess the similarity between the model dancer and the novice performer. A prototype learning platform involving a virtual 3-D teacher allowed a student to imitate and repeat dance movements in short sequences, which were then recorded and compared with those of the virtual teacher, thus providing feedback to the students on the specific LMA component of the performance that needed improvement. Using principles derived from the design of computer games, the platform adaptively adjusts feedback to the needs of the student.[32]

Dance notation systems have also been used to "generate anthropomorphic motions in robots or animated avatars." Using Labanotation and Laban Movement Analysis, Naoko Abe and his colleagues designed a motion-generation program to instruct humanoid robots to perform "tutting," a simple dance sequence involving the upper body. After notating the dance, they translated the Laban score into the framework of a motion-generation program called "Stack of Tasks." Humanoid robots use about thirty motors to move, and are operated either at a distance "by transferring human motion-capture data to the robot" or through internal controls employing "computational programming."[33] Stack of Tasks considers each action the robot must perform, establishes a hierarchy of tasks, and defines their succession.

Abe and his colleagues used a visual 3-D display to determine how the Laban score could be executed and found that information was lacking to unambiguously define the robot's movement, primarily because humans move with more flexibility and fluidity than motor-driven robots. The researchers concluded that dancers and roboticists conceived movement in entirely different ways, and that the Laban score did not provide the necessary information "in terms of motor control" required to produce "straightforward motion generation in a robot." In their view, "The main issue concerning movement in robotics is the movement in motor-control level, and not the movement in the physical space, while Laban notation does not give any information concerning the movement in motor control level, even if it gives all information pertaining to physical space. The point of view on the generation of movements is thus completely different in the two fields."[34]

Computer choreography and performance in the late twentieth century

The use of computers to design choreography expanded during the 1970s and 1980s, primarily in academic settings. Merce Cunningham became the first well-known choreographer to be interested in how computers, with their enormous capacity to process information and generate random numbers, could help in choreographic design (Box 2). His collaboration with university researchers stimulated other choreographers to experiment with the electronic tools that became available during the last decades of the twentieth century.

Box 2: **Merce Cunningham and Computer Choreography**

Well before becoming aware of Noll's computer choreography experiments, Merce Cunningham had used the *I Ching* to introduce elements of randomness into his choreographic designs. By 1991 he had begun to explore LifeForms, a program created in the 1980s by Thomas Calvert, one of the founders of the software company Credo Interactive, who was associated with the Laboratory for Computer and Communications Research at Simon Fraser University. The version of the program used by Cunningham determined the position of dancers on the stage for segments, of up to two-minutes duration, which were joined to create longer dances. Cunningham staged *Trackers*, one of the first choreographies he created with the program, in New York in March 1991. *CRWDSPCR*, another choreography created with Dance Forms—a program successor to LifeForms—remained in the repertory of the Merce Cunningham Dance Company between 1991 and 1999, and was revived in 2007.[35]

As Cunningham put it during a 1997 interview, the computer program provided "a visual way of looking at movement … one could use it as a tool. I use it as a way to look at movement from another point of view. I use it primarily to place movements on the figure and then put them in the memory, so … I don't have to write them down.… I have them in this visual form and can bring them back when I want to work on a piece with the dancers."[36]

Experiments to design computer-assisted choreographies multiplied during the last decades of the twentieth century. A team at Simon Fraser University developed the first widely used programs for recording, interpreting, and visualizing dance scores in computer monitors; another, at the University of Pennsylvania, employed film recording, dance notation, and interpretation of dance scores to model human movements and develop animations; researchers at the University of Waterloo devised programs to interpret dance notation and show movements on screens; and a team at the University of Iowa focused on developing programs to teach Labanotation and analyze dance scores.*

A long-term research effort that started in 1971 at the University of Sydney, the Choreology Project, led to the development of a programming language capable of representing dancers' movements. The researchers worked with several subroutines to generate different types of movement and later linked the program to Benesh Notation to generate animated figures that performed dance scores. By the end of the 1980s, they had developed a system capable of displaying various moving body parts on a screen and registering them on videotape. While they acknowledged that "the final system [was] too slow and expensive for teaching purposes and most practical applications," Don Herbison-Evans and George Politis expected that "the design of specialized chips" would "raise the speed and lower the cost, to bring it within a range that is viable for dance schools within a few years."[37]

Starting in 1969, computer graphics pioneer John Landsown began a series of computer-choreography experiments that lasted for more than a decade. He aimed to determine whether or not the computer could completely construct and score a dance by combining "various procedural techniques for generation" and "established notations for scoring."[38] His programs defined the moving parts of the body together with their direction, level, and timing. To build a sequence of movements he created a decision tree of possible transitions, assigning probabilities to each branch. Producing several short dances, Landsown felt gratified by results that pleased and challenged audiences and dancers alike.

Landsown realized that "in order to achieve results which even remotely matched the efforts of a human choreographer in quality and scope," he would need to enrich the computer's vocabulary and enhance the subtlety of its notation program. This led him to modify his approach to design an algorithmic computer program that provided "frameworks which … outlined only the important 'peaks' of movement rather than the complete movements themselves."[39] Apart from solving some notational and computational problems, this restrained approach allowed Landsown to open the space for the choreographer and the dancer

* George Politis, *A Survey of Computers in Dance* (Technical Report 311, Basser Department of Computer Science, University of Sydney, 1987). The heavy involvement of universities in attempts to use computers in choreography prompted the following reaction: "Almost all computer applications in dance have been developed in academia, out of touch with the traditional ways in which professional artists have worked." Peggy Brightman, "Computers, Choreography and Creativity," *Knowledge-Based Systems* 3, no. 1 (March 1, 1990): 43, https://doi.org/10.1016/0950-7051(90)90040-O.

to insert their own ideas between peaks or key frames proposed by the computer program.*

Between 1973 and 1976 Brazilian choreographer Analivia Cordeiro pioneered the use of computers and television in the design and performance of dance. Her first works sought to facilitate the fluidity of interaction of the choreographer, the television director, the dancers, and the computer.[40] The computer program consisted of subroutines that defined the displacement, body positions, and tempo for the dancers; as well as the camera angle, focus plane, and visual effects, and change of camera for television. According to Cordeiro, "By selecting components and establishing formal relationships between them, the choreographer structures an interactive dance-TV system. In this way he creates the algorithm which will generate the choreography he imagined."[41] The computer program devised by Cordeiro generated a set of instructions for the dancer, the cameramen, and the TV director, with the dancer using his or her individual expression to define additional elements, such as muscular effort and fluidity of movement, that remained unspecified by the computer program.[42]

In the mid-1980s, a survey by computer scientist George Politis identified close to one hundred articles on computer choreography and related subjects. In spite of two decades of "much research, experimentation and innovation of applications of computers to dance," he did not voice an overly optimistic view of the future of the field. He expected slow advances and increasing focus on small-scale applications. However, he also anticipated that if research continued unabated and hardware became affordable, then dancers could "obtain a useful product or two by the end of the century." His conclusions nearly hit the mark, although later developments would provide dancers with a wider variety of computer tools and electronic devices that expanded the field in unforeseen directions.[43]

A 1989 book edited by dance instructor Judith Gray gathered contributions from a dozen academic researchers who dwelt on notating dance, articulating the language of human movement, programming a robot to dance, describing and analyzing tap dance sequences, examining the biomechanical impact of dance movements, using motion detectors in dance instruction, capturing dance images, and employing computerized lighting designs. Gray anticipated future directions for the convergence of information technology and dance, ranging from interactive displays, computerized dance models, and holographic images of dancers onstage, to electronically

* In a speech delivered twenty years later, Landsown reviewed his experience with computer choreography and concluded, "It is clear that computing can assist choreographers in a number of ways, although there is much to be done to make computing systems more congenial to their potential users." John Lansdown, "Computer-Generated Choreography Revisited," in *4D Dynamics Conference on Design & Research Methodologies for Dynamic Form*, ed. Alec Robertson (Leicester, UK: De Montfort University, 1996), http://www.4d-dynamics.net/4DD/guest-jl.html.

controlled lighting and stage-design configurations, advanced software for dance instructions, and artificial intelligence software for designing choreographies. She concluded optimistically, "The continued collaboration of dance and computer technology in higher education will likely change the face and perception of dance as an art form."[44] Yet, a skeptical review of the book wondered whether the research and applications of information technology to dance would "dehumanize dance," diminish the excitement, and undercut the participation of humans.[45]

During the late 1980s, Tamas Ungvary, Simon Waters, and Peter Rajka of the Royal Institute of Technology in Sweden developed a computer-based compositional and choreographic system that allowed direct transfer between and joint interpretation of music and dance scores. The system consisted of two major components that recorded dance (Motographicon) and music (Macrosticon), linked dance movement with a music score, and depicted both graphically. From the movement information generated, they obtained the outline of an experimental choreography, for which they composed a short electroacoustic piece. From this they produced a one-minute dance/music work used "to demonstrate the movements of an animated figure on the computer screen," accompanied by electronically composed music. At a subsequent stage, they employed signal-processing software to analyze the music, used amplitude and frequency data to infer dance movements, and translated them into choreography using the Motographicon. A choreographer interpreted and adjusted this material, which the system then transcribed into the form of a joint dance and music score.[46]

In the mid-1990s, computer scientist James H. Bradford and dance teacher Paulette Côté-Laurence developed an experimental computer expert system to codify human knowledge and experience in the design of choreography. The system consisted of two main programs: a "Rule Setter" examined, recorded, and processed probabilistic "if-then" choreographic rules; and a "Dance Maker" used these rules to generate a sequence instructing dancers how to move over time. A dance script resulted that defined at each moment the position of dancers onstage, the direction and speed of displacements, and the type of body movement involved (pivot, bend, turn, and so on). While the authors did not report staging these dance scripts, they saw the potential of their choreography expert system to extend the range of human creative process toward the unfamiliar.[47]

In the late 1990s Carla DeSola created a dance for eight members of her company using a commercial version of LifeForms 3.0. DeSola selected a spiral floor pattern, chose poses for each dancer, and created a sequence of movement transitions after testing the poses out on her own body. Projecting the resulting choreography on a full-size screen, the choreographer taught the dancers the poses and spatial displacements. She experienced the process as collaboration between computer and choreographer, with one improvising and the other evaluating and selecting specific movements. DeSola believed the process stimulated her to go beyond her "habitual patterns" and to devise "a richer choreographic vocabulary."*

By the end of the 1990s, even a dance history conference held in the Netherlands was covering issues such as "Smooth Rotational Motion in Computer Choreography Systems," or how to use computer animation techniques and mathematical treatment to display rotation in three dimensions; and ARTBODIES, "a programming approach for simulating and controlling human figures by computers." ARTBODIES's software modules focused on creating three-dimensional artificial bodies that could move according to a series of commands, so that the user/choreographer could write, "play around with," evaluate, and rewrite a script, until it suited his or her taste. The system aimed to show "the fun and versatility of computer choreographical design."[48]

By the end of the twentieth century, the use of information technology in dance, and specifically computers in choreography, had demonstrated its potential viability. Yet, several obstacles to smooth and fruitful interactions between information technologists and dance professionals remained. Apart from notational difficulties, the state of the art in electronic devices did not allow full capture and processing of the complexity and intricacies of human movement. Moreover, in designing computer programs and interactive tools, scientists had not sufficiently understood, or taken into account, the creative processes of choreographers (Box 3).

Box 3: **Computer Choreography and the Creative Process**

Choreographer Peggy Brightman summarized the potential and pitfalls of computer choreography during the last decades of the twentieth century, highlighting the collaborative nature of the creative process, much as it had been intuited in the early experiments of the 1960s:

> As dance artists use the computer as a tool, they must necessarily learn more and more about their own creative process … Perhaps the most interesting aspect of computer-as-assistant is the process of having to become conscious of one's own creative process, in order to be able to express it in symbolic form.… Both choreographer and dancers can participate in this process, which has a controlled framework, set by the parameters selected. Freedom within constraints is what the computer offers the choreographer who learns to think of movement as rule-based and parametrically defined.… The artist who can adapt technology to his own unique needs will open many new doors to creativity.[49]

Yet, echoing and amplifying the viewpoints expressed by the pioneers of computer choreography, she clearly pointed out that the designers of computer programs should accept that the ultimate artistic decisions must remain with the choreographer. In essence, computer choreography is a dialogical process, with the computer scientist offering a palette of variables and algorithms, and the choreographer, his or her medium-based knowledge and aesthetic judgment.[50]

* Genevieve Katz, "Life in the Fast Lane," *Dance Magazine* 72, no. 11 (1998): 74. Katz notes that another user of LifeForms, Jimmy Gamonet, Peruvian-born ballet master of Miami City Ballet, finds that the computer program sometimes designs impossible movements that require the choreographer to interpret the results.

Computer choreography in the twenty-first century

At the turn of the century, the pace of innovation in electronics and computer sciences accelerated, which expanded considerably the range of options for using information technologies in the performing arts—and specifically in the composition and staging of dances. Roughly following "Moore's law" the processing speed and data storage capabilities of microprocessors increased exponentially, which eventually allowed the use of highly powerful computers to explore the application of genetic algorithms, neural networks, learning software, and other artificial intelligence tools to the arts.* Together with miniaturized motion-capture devices, large visual displays, lighting and sound control apparatuses, and advances in software programming, these enhanced capabilities altered radically the processes of dance creation and performance, led to the commercial development and practical use of computer software in the design and staging of choreography works, and even facilitated the widespread dissemination of smartphone and tablet-based applications for experimenting with choreography.

The first decade of the twenty-first century marks an inflexion point, with choreographers and dancers beginning to fully exploit the capabilities of new electronic devices and software programs. Combinations of dancers, images, objects, lighting, and sounds moving and reacting to one another—both in predetermined and improvised ways—all under the joint control of artists and computers, led to performances that challenged established habits of thought in choreography. As shown in Box 4, some initiatives still focused on how to record, interpret, retrieve, and teach body movements, but others went beyond assisting choreographers in their creative processes; the new tools allowed the development of new modes of artistic expression and took human-machine interactions to new levels.

Box 4: **Registering, Representing, and Teaching Dance in New Ways**

In the early 2000s a group of researchers at the University of Vienna conducted a project focused on "the complex movements of the whole body" in Western classical ballet usage. The idea was to develop a tool to support "the (semi)-automatic recording and annotation of dance sequences," using video cameras and body sensors to track record a dancer's movements, Labanotation to register them, and optical tracking algorithms to reproduce the dance at different rates, up to more than 400 frames per second.[51]

Focusing on a single dancer, Chi-Mi Hsieh developed a sophisticated way of manipulating representations of body movements at the Informatics and Artistic Creation laboratory of the Grenoble Polytechnic Institute. He developed a computer program to bridge the gap between the dancer's functional movement and intention considering the interactions of the body and the environment, and taking into account the resulting movements perceived by the audience. To achieve this, he constructed a set of dynamic particle models called "dance verbs" to account for actions such as "to rebound," "to jump," "to

* According to Gordon E. Moore, "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. . . . Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years." Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics* 38, no. 8 (April 19, 1965): 114. Moore's projections held true for several decades more.

flip," and "to wave," some of which could be further broken down. The vehicle for describing these dance verbs was a discrete computational algorithm, based on representations of "two kinds of forces: elasticity and viscosity" that took into consideration internal stimuli and external resistance. He further dissected the action verbs to account for the origin of the movement, its propagation in time and space, and the recovery by means of which the dancer finds a new balance. In a joint article with professor Annie Luciani he argued for the importance of creating a library of dance verb models on which to base choreographies.[52]

"Terpsichore" is a multimedia interactive computer choreography program for ballroom dance education and training, created in 2012 by computer scientist and musicologist Nigel Gwee, employing a search engine and a knowledge database of standard ballroom figures. Using the "International Standard Ballroom Syllabus" compiled by Gwee, the user/choreographer chooses a set of dance movements for the program to work with, the type of algorithmic search method (exhaustive, greedy, randomized), the category of dance figure (foundational, intermediate, advanced), and the length of the dance sequence. Terpsichore randomly creates a number of "amalgamations" of dance movements, and then applies evaluation functions using degree of difficulty and variety criteria to choose a dance sequence and display the results. In a subsequent paper and focusing on individual body movements, Gwee also used mathematical concepts to characterize categories of dance problems and relate them to other computer science, mathematics, and operations research problems.[53]

Pushing the boundaries: Information technology enters the stage

With a few exceptions, most of the experiments on computer choreography until the turn of the century focused on supporting the creative process of choreographers primarily by using random number generators and mathematical selection rules to increase the range of movement options for him or her to consider. The increased availability of inexpensive and powerful electronic devices opened up the possibility of designing dances in which performers interact in real time with electronically mediated visual, sound, and lighting components. As a result, the work of Michael Klein, Dawn Stopiello and Mark Coniglio, Analivia Cordeiro, William Forsythe, and Kate Siccio—as well as that of Katherine Isbister and her colleagues on choreographed computer games—began to push the boundaries of choreographic design and performance.*

ChoreoGraph, a software platform developed by choreographer Michael Klein in the late 1990s, sought to help choreographers to "structure and control the various components of any performance events." It consisted of several movement modules, which were assigned "weight values" to determine how frequently a particular movement should appear, but also "refresh settings" to prevent one or several movements from repeating too often. The software platform used standard mathematical and statistic tools, together with custom-crafted rules, to generate graphic representations of dance sequences. The system allowed dancers "to build strategies, be cre-

* Cirque du Soleil performances combining improbable acrobatic feats with special sound, lighting, and mechanical effects onstage offer an embryonic intimation of what may be achieved in the future in the intersection of human movement and advanced technology. See Suzanne Rivard, Alain Pinsonneault, and Anne-Marie Croteau, "Information Technology at Cirque Du Soleil: Looking Back, Moving Forward," Thirty-Second International Conference on Information Systems, Shanghai, 2011, 1–11, https://pdfs.semanticscholar.org/a375/5a66f5c81e4b9da616cac14d1b11ffdfbb6f.pdf; Michael Venables, "The Technology behind the Las Vegas Magic of Cirque du Soleil," *Forbes*, August 30, 2013, https://www.forbes.com/sites/michaelvenables/2013/08/30/technology-behind-the-magical-universe-of-cirque-du-soleil-part-one/.

ative and find solutions beyond physicality.… a process that allows the dancer's mind to be 'choreographed' and not just the body."[54] Klein saw *Solo One*, the first dance created by ChoreoGraph, staged in 1998. He proceeded to design a more elaborate version of the program for the creation of *Duplex*, a choreography staged in 2002, which sequenced improvisational tasks, rather than fixed choreographic phrases.

An experimental dance group established by Stopiello and composer Mark Coniglio in the mid-1990s sought to "question the deepening entanglement between human beings and new technology."[55] During the following two decades they produced more than two and a half dozen choreographies combining digital lighting and music effects with dancers' movements. For example, *Swarm* involves the audience in the process of creating the sonic and visual landscapes that affect the movement of dancers onstage.[56] Coniglio and Stopiello developed two software tools: Isadora, which integrates aural and visual images with dancer movements and allows real-time control of digital videos, lighting effects, audio files, and robotic devices; and MidiDancer, which uses body sensors to feed dancer movements into an offstage computer that subsequently processes the movements using Isadora.[57]

Following up on her earlier experiments on computer choreography and movement notation systems, in the mid-2000s, Analivia Cordeiro sought to create "a dialogue between corporal conscience and electronic media" as a response to the pervasiveness "and continuous use of electronic instruments that impregnate human relations."[58] She developed a complex approach that integrated dancer movement, motion capture, video camera, projector, and computer to produce performances that combined live dancing with images on screen. Sensors on the dancer's body generated the images; a computer processed them; and an onstage operator acted as video jockey, modifying and projecting the images onto a screen behind the dancer.*

An Ohio State University team of researchers explored a different approach to the relations between computers and choreography. After four years of collaborating with the Forsythe Company, in 2009, they launched an interactive web project titled "Synchronous Objects for *One Flat Thing, reproduced*," based on a thorough analysis of one of William Forsythe's choreographies *One Flat Thing, reproduced*. Forsythe remarked apropos of this experiment, "Choreography is a curious and deceptive term. The word itself, like the process it describes, is elusive, agile and maddeningly unmanageable."[59] The research team sought to answer questions like

* Analivia Cordeiro's work, which shows several graphic projected interpretations of a dancer's movements to Dave Brubeck's "Unsquare Dance," can be accessed at: Instituto de Matematica Pura e Aplicada in Rio de Janeiro, "Unsquare Dance," 2007, https://www.visgraf.impa.br/unsquare-dance/.

"What are the organizing structures behind a piece of choreography? How can these be made visible using interactive screen-based media? And what is the best way to communicate them?"[60]

The dance involved the concrete physical actions of dancers dragging and moving around twenty steel tables, and the "team set out to discover, analyze and chart the work's 'deep structure,' the scientific and mathematical mechanisms churning beneath its surface."[61] According to Norah Zuniga Shaw, one of the creative directors of the project, they succeeded in developing a "choreographic resource" that could be applied in fields beyond dance. She envisaged possible applications in architecture, design, and geography, where insights related to the time-space mapping of human movement could prove useful.[62]

Choreographer Kate Sicchio explored the interactions between programming software and choreography. Some of her dances project computer code on a screen or on the floor of the stage to give real time directions to the dancers, who follow, anticipate, and interpret them in the moment, thus "hacking" computer instructions in their performance. Sicchio's 2014 *Hacking the Body 2.0* exhibited onstage a large screen, a laptop, and a programmer who wrote and displayed sequences of individual body movements for two dancers. The dancers complemented these instructions by making decisions about their floor patterns. Another of her choreographies used motion sensors to provide dancers with feedback on their body positions, allowing them to react to their own movements.[63]

A rather different take on the interaction between information technology and dance movement emerged from the design of *Yamove!*, a "dance battle game" that coordinates the dance movements of two or more players using a game app designed for iOS devices. According to game and computer interface researcher Katherine Isbister and her coauthors, the idea was to choreograph "meaningful and natural movement–based interaction," first for two players, who received instructions on their smartphone screens.[64] They tested the game in different settings and found that players enjoyed attempting to synchronize their movements to increase their scores.

A subsequent version of the game used technology "to support rather than entirely sustain social interaction and play," transforming playful interaction into a dance battle.[65] In addition to the characteristics of the game itself, with its rules and goals and input/output interface, the new version incorporated social and spatial elements, specifying the position of the players in space, the roles assigned to them, the behaviors of spectators watching the game, the placement of physical artifacts, and the contour of the play space itself. The game became a three-round dance battle between two pairs of players, with the running scores posted in real time on a large screen to stimulate competition. Over time *Yamove!* "evolved into a multi-person, multitechnology dance battle game that included a live MC [Master of Ceremonies] as well as a carefully crafted social atmosphere."[66]

Forty years after the initial attempts to forge links between information technology and dance, in 2007 journalist Emily Macel described the state of the art in the following terms:

> Computers have invaded the scene. Stages become moving images—cars crash or rain falls—and the dancers perform through the elements. Bodies are duplicated, triplicated, contorted, and then paired with themselves through the power of projection. And digital dancers bend, turn, and jump on computer screens as they are choreographed on an X- and Y-axis before ever reaching the stage. Welcome to the age of dance and technology. It's a magical place. It isn't a "new" era, but an ever-evolving one that is inspired by dance artists past and present.[67]

Clearly, advances in electronic processors, body movement sensors, visual displays, storage devices, and program software had helped choreographers to create novel dance expressions.

Genetic algorithms, neural networks, and artificial intelligence as creative catalysts

By the second decade of the twenty-first century information technology had become a powerful creative catalyst for artistic creativity.* Genetic algorithms, neural networks, and artificial intelligence opened up new ways of designing and performing dance. Rather than mapping out new means of expression or creating, via random number generators, novel movement sequences—both involving rather detached interactions between choreographers and computers—these new developments intertwined algorithms, neural networks, and other artificial intelligence tools with the products of human imagination. As a consequence, joint choreographer-computer initiatives began to morph into active and fruitful partnerships.

Choreographers and computer scientists who have explored the use of advanced information technologies as creative catalysts include Kristin Carlson, Thecla Schiphorst, and Philippe Pasquier; Marc Downie; Wayne McGregor and Scott deLahunta; François-Joseph Lapointe and Martine Époque; Pablo Ventura; and Luka Crnkovic-Friis and Louise Crnkovic-Friis.

Carlson, Schiphorst, and Pasquier describe *Scuddle* as a movement catalyst for contemporary choreography, "supporting active reflection

* According to Kristin Carlson and her colleagues, throughout history, artists have relied on the concept of *creative catalysts*. Two examples are Merce Cunningham's use of the *I Ching* and his application of chance procedures to the creation of choreographic structures. Such catalysts are "often used to explore ideas in new ways and to push the self beyond known answers." Kristin Carlson, Thecla Schiphorst, and Philippe Pasquier, "Scuddle: Generating Movement Catalysts for Computer-Aided Choreography," in *Proceedings of the Second International Conference on Computational Creativity*, eds. Dan Ventura et al., 2011, 123, 128, http://computationalcreativity.net/iccc2011/proceedings/index.html.

on creativity through awareness of the decision making process."[68] To achieve this, *Scuddle* generates incomplete movement data, stimulating the choreographer to explore multiple patterns from the results. The genetic algorithm creates a large number of random possible movements, selects those that fit certain pre-established criteria, and repeats the process for a predefined number of iterations, or until a certain fitness threshold is achieved.[69]

Motivating computer scientist Marc Downie was the idea that "the marriage of dance and interactive image" had been an elusive dream for decades. Using biological metaphors and artificial intelligence tools, he proposed a "theoretical, technical and aesthetic framework for the innovative art form of digitally augmented human movement." In collaboration with choreographers and composers, Downie developed several interactive installations with musical accompaniment, showing that ample room exists for a genuine and constructive dialogue between digital art and dance. Such dialogue is enabled because, according to Downie, in choreography "algorithmic concerns meet the realities, constraints, and meanings of the human body and the eyes of the audience."[70]

In the early 2000s, British choreographer Wayne McGregor and researcher Scott deLahunta began an "interdisciplinary research project aiming to broaden understanding of the unique blend of physical and mental processes that constitute dance and dance making." They used artificial intelligence algorithms to solve choreographic problems and to augment McGregor's creative decision-making process. Later, in collaboration with Downie, they developed the Choreographic Language Agent (CLA), a system that allows new algorithms and control structures to be rapidly created and revised in order to "meet the realities of collaboration, rehearsal and improvisatory choreographic practice."[71]

As McGregor's interdisciplinary dance research projects evolved over time, CLA led to the creation of *Becoming*, an interactive digital object to support dance making in the studio, and *Atomos*, a dance inspired by the emotional states of dancers. The latter involved the use of "emotional wearable technology," consisting of wristband sensors and computer software that made mental states visible, as well as digitally designed and printed Lycra skins inspired by each dancer's biometrical data.[72] In addition to work derived from CLA, McGregor and his team have generated a variety of choreographic thinking tools to enhance choreographic skills and a series of installations to explore interactions among mind, body, and movement.[73]

Developed by biologist and choreographer François-Joseph Lapointe, Choreogenetics takes a dance sequence as input, generates new dance sequences through mutation, evaluates the results with different fitness criteria, and repeats the process, only stopping after a predefined number of iterations, or until it meets a specified aesthetic criterion. Based on a "mother" sequence, the program generates "daughter" sequences through substitution, insertion, deletion, inversion, translocation, and conversion algorithms. Choreogenetics creates dances for several performers by developing sequences that interact with each other during the mutation phase through duplication, extinction, horizontal transfer, and hybridization procedures.[74]

The program creates choreographies by comparing the mother and daughter sequences at each iteration and selecting the one that fits best according to one or more of five criteria.* Noting how common it is "for human performers to share the stage with virtual dancers," François-Joseph Lapointe and choreographer Martine Époque described how they used Choreogenetics, together with the LIFE animation software developed at the University of Montreal, to create *Tabula Rasa*, a choreographic work for twenty-two dancers and one virtual dancer, which was shown at various locations around the world.[75]

Computer scientists Sangeeta Jadhav, Manish Joshi, and Jyoti Pawar developed a program to discover new dance steps and body movements in Bharatanatyam, a classic Indian dance, with the objective of providing choreographers with "a list of unexplored, novel dance steps to fit [into] a single beat." Using a catalogue of Bharatanatyam's fundamental postures and movements, their program generated representations of the positions of the head, hands, waist, and legs at each moment in time. They used thirty "dance position vectors" (defined as a combination of eight attributes for each hand position, five for each leg position, two for the head position, and two for the waist) to depict a single Bharatanatyam position at the end of each beat. The suitability criteria of their genetic algorithm accepted variations neither too far from nor too close to the traditional positions; that is, it sought an element of surprise with slight deviations from the ideal traditional dance step.[76]

Using stick figures to display the thirty attribute vectors, the researchers engaged a trained Bharata Natyam dancer to try out the computer-generated positions. Dance experts evaluated most of the twenty-five images generated by the program and reproduced by the dancer as either good or just right. Jadhav, Joshi, and Pawar concluded that the choreographer should imaginatively respond to the output generated by the genetic algorithm, rather than replicate the posture exactly: "The hand, leg, or even the unique

* The five criteria stem from (1) a neutral model that accumulates variation in subsequent iterations; (2) a user-defined or audience-mediated process that requires human intervention; (3) an approach, based on information theory, that assesses the information, entropy, and complexity of the sequences; (4) aesthetic considerations predicated on order, symmetry, repetition, and balance; and (5) a coevolution model that selects between mother and daughter sequences based on comparisons with a third sequence.

head position suggested by the system for a single beat will allow more room for unique choreography and creativity."[77]

For more than two decades, choreographer and performer Pablo Ventura intermixed choreographic techniques and custom-designed software to create dances that simulated "the operational logic of computers" and interacted with "computer-generated dance and media elements."[78] Encompassing all aspects of staging dance and scenography, Ventura's artistic endeavors sought to innovate through "the tight integration of aesthetic motivations, conceptual reflections, and technological experimentation." He aimed to inspire choreographers to experiment with "generative and machine-like forms of creativity"—for example to apply algorithms to their choreographic processes—and to incorporate "digital and responsive media."[79]

Ventura posed questions such as, "How can human beings be dehumanized to such a degree that they can be operated like machines? What properties must a machine fulfill to evoke associations with a living organism? What specific human qualities remain even if the dancers' appearances and movements deviate as far as possible from their natural characteristics? Can human beings and machines coexist symbiotically or will one of them eventually overcome the other?"[80] Starting in the late 1990s Ventura attempted to answer these questions by resorting to a wider and wider range of information technology concepts and devices, while creating a series of computer-based choreographies. In *Deux et Machina* (1997) a virtual avatar and a human dancer interacted onstage. *MADGOD* (1999) and *MADGOD 2.001* (2000) used video projections on the stage and on the dancer's body, as well as distorted poses that broke the conventional use of space in dance. *Zone* (2001) used numerical sequences such as the Turing Chain and the Pascal Triangle to create rhythmic structures and sequences of movement performed jointly by robotic and human dancers. Finally, *De Humani Corporis Fabrica* (2003–2005) comprised three dances inspired by Andreas Vesalius's anatomy book from the sixteenth century; the last of these involved a specially designed performing robot.

Between 2009 and 2014, Ventura's charting of the relations between humans and machines continued. Three new dances—*2047*, *Dancescapes*, and *Heliopolis*—explored the ambiguities between human and nonhuman stereotypes, the cultural implications of combining software-generated and idiosyncratic dancer movements, and dancers' control of a polyphonic composition by triggering and modulating the playback of sound material through both their movements and their engagement with "motion-sensitive zones on stage."[81]

Artificial intelligence expert Luka Crnkovic-Friis and artistic director and choreographer Louise Crnkovic-Friis developed *chor-rnn,* a system consisting of an artificial neural network* and several computer programs to capture motion from sensor data and extract the essential features of dance movements using deep learning algorithms.[82] *Chor-rnn* records the movements of a dancer's body using sensors, a 3-D camera, an infrared camera, and associated software to track the joint movements of a dancer-choreographer. The recurrent neural network processed several hours of motion data codified in the form of a 75-dimensional tensor (25 joints x 3 dimensions), which was used as input into a Graphics Processing Unit server with ample memory and a speed of 27 teraflops, in order to train the neural network.† The results were displayed visually as graphs and animations, and after several training runs lasting about six hours, the neural network recognized relative joint positions and basic movements; after forty-eight hours it recognized the main features of the language, style, and overall theme of the dance created and performed by a particular choreographer.

Crnkovic-Friis and Crnkovic-Friis concluded that their system "produces novel, anatomically feasible movements in the specific choreographic language of the choreographer whose work it was trained on." They also suggested that *chor-rnn* could serve as a tool in at least two ways. In the first case, "the artist choreographs a sequence, … [c]hor-rnn takes [it] as input and produces a new sequence … as a continuation," which then becomes input for the choreographer, and so on; therefore, artist and computer program collaborate as each one builds on what has come before. In the second case, the artist "reinterprets" the sequences specified by chor-rnn and feeds these reinterpretations back into the system. By repeating either process to his or her satisfaction, the result would be "a computer inspired human made choreography."[83] The researchers anticipate that, although developed for a single dancer, *chor-rnn* could work for several dancers; it could interact with music to generate choreographies; and it could even help to construct a symbolic language spelling out the style, syntax, and semantics of choreographic works.

Two additional, early twenty-first-century computer choreography experiments do not fit into the paradigm of human creativity catalysts. Dance teacher Matthew Gough proposed considering computers as

* An artificial neural network is an electronic device, loosely based on the structure of connections between brain cells, in which each node represents a neuron that processes information from other nodes and passes it on to subsequent nodes. They are used in a variety of tasks—such as machine translation, speech recognition, playing games, and computer vision—that require a computer to learn by receiving, storing, and processing a large amount of data.

† One teraflop is a trillion floating-point operations per second (flops)—several orders of magnitude faster than the IBM System 360/mainframe that we used in our 1967 computer choreography experiment, which processed up to a million flops per second. Choreographic programming feats like those of Crnkovic-Friis and Crnkovic-Friis require huge electronic storage capacities and extremely fast processing speeds—impossible before the availability of commercial supercomputers in the early twenty-first century.

autonomous creative agents, capable of designing dances with limited human intervention. Gough's "epikinetic composition" approach is related to computer models that generate "raw, unstable movement rather than controlled motion," analogous to the adaptive motion-control algorithms in aeronautics, which allow "unstable platforms (such as the F-117 'Nighthawk') to maintain level flight and keep the aircraft 'in the air.'"[84] In Gough's model, different program modules improvise dancer movements, reconfigure them to satisfy biomechanical limitations, register and store performance motions, filter them through the use of composition techniques, allow for further improvisational embellishment, and incorporate additional stimuli (music, images, motion capture) to create choreography.

Gough aims to remove any emotional content from the dance design process, arguing that dispensing with the use of existing movement data is "an essential requirement for any choreographic software designed to automate and or stimulate the choreographic process." In his view, the loss of human intercession could foster the development of "new narrative forms" and physical techniques that would nonetheless remain embedded in physical reality. Gough claims that his system would not replace dancers and choreographers because "virtual dancers can and will exist alongside their physical counterparts, illuminating new narratives and forms beyond our conceptually biased imagination. A loss of authorship to the computer should only strengthen artistic resolve and refresh creative energies."[85]

In a second example of computer choreography that skirts human intervention in the process, University of California machine-learning researchers Chris Donahue, Zachary C. Lipton, and Julian McAuley created an artificial neural network to develop step charts containing graphic indications of where to place the feet for players of different skill levels of the video game franchise *Dance Dance Revolution*.[86] In this game, "players perform steps atop a dance platform, following prompts from an on-screen step chart to step on the platform buttons at specific, musically salient points in time."[87] Preparing step charts in ways that capture the precise rhythms of music is an exceedingly time-consuming task. Using as input more than thirty-five hours of annotated music and 350,000 steps designed by two choreographers, Donahue and his team trained an artificial neural network to create several complete *Dance Dance Revolution* step charts to be shown on a screen for players to follow. They first converted music into "visual representations of audio frequencies," which allowed the neural network to identify features like pitch and rhythm; next, they used a step placement algorithm that first sliced the song into minute samples and then determined the location of particular steps based on "relevant audio features."[88] Finally, a selection algorithm mapped the selected steps for each video-game player in a complete score.

Explorations beyond computer-generated choreography

Science, mathematics, and technology have often served as sources of inspiration and imagination for artists. The contributions of science, technology, engineering, and math (STEM) fields to choreography go beyond the application of advances in information technology or the use of computers as creativity catalysts and design tools. In today's interdisciplinary landscape, theoretical and experimental physics provide metaphors and images to inspire choreographers; electronic sensors feed real-time body and ambient data into dance performances; and mathematical and statistical techniques allow close scrutiny of dancer movements, especially in relation to music.

Several choreographers have used concepts and technologies derived from physics in their work.[89] According to dance researcher Joyce Morgenroth, Elizabeth Streb, founder of the Streb Lab for Action Mechanics, has choreographed dances employing "highly engineered equipment," which has facilitated her investigations of human movement "in a systematic, methodical way" and fueled her fascination with "the forces exerted by gravity and impact." Adopting the scientific method in her approach to dance design, Streb uses concepts from physics in her exploration of space, time, and the forces acting on our bodies.[90]

Karole Armitage neatly summarizes her choreographic vision as "how to… make ballet *look* like what we know of physics today? That's my job.… I can capture its poetry."[91] She has grounded choreographies on theoretical physics concepts—such as distortions in the fabric of space-time, the multiple paths that particles can traverse, and multilayered loops—to create dances with complex sequences of body movements and spatial displacements. *Schroedinger's Cat* (2000) was based on the idea of quantum superposition. *Connoisseurs of Chaos* (2008) derived spatial conceptions from the study of fractals. And *Three Theories* (2010) used relativity, quantum mechanics, and string theory as metaphoric sources of inspiration.

Amanda Miller and Tobin Rothlein, artistic directors of Miro Dance Theatre in Philadelphia, have also created choreographies based on the work of theoretical and experimental physicists. According to Rothlein, "Just as we artists continually break things down during rehearsal to reach some truth and simplicity in performance, physicists break down matter to discover simplicity and truth in the universe."[92] A visit to Fermilab, a particle physics laboratory, inspired Miller to create *Principles of Uncertainty*, an outdoor dance that mimicked the trajectories of colliding particles in an accelerator. According to Miller, dancers "had to think about how much spin they would have after a collision, as well as their rate of decay. After each collision the dancer would spin out into the crowd, follow a trajectory that could change if they came in contact with another dancer, and… decay to complete stillness before going back to the starting point to begin a new cycle." *Spooky Action*, another Miro dance, used entanglement, a quantum physics concept, to define the movements of two dancers—separated in space—whose movement, nonetheless, appeared to balance or influence one another from a distance.[93]

Thecla Schiphorst choreographies rely on performance methodologies that focus on technologically mediated experience made possible by "ambient and wearable technologies: technologies that live close to the body."[94] In various staged works, performers have reacted to their heart rates and breath rhythms recorded with physiological sensors and transmitted through wireless networks embedded in garments. The idea was to capture their body state and feed it back into the performance process.

In another experiment, sensor bands wrapped around the chest captured breathing movements, and the performers used "group breath … as an interface for interaction" through vibrators and speakers "embedded in the lining of … sensually evocative skirts." Schiphorst has also explored the interactions between dancers and "pliable, tactile, throw-able soft objects" constructed with electronically enhanced surfaces.[95] A Laban-based movement analysis process allowed Schiphorst to interpret the "varying qualities of touch and motion trajectory" in order to choreograph dancer movements exploring the notion of social intimacy through techniques grounded in "somatics and performance practice." Her work in technologically mediated performance led Schiphorst to conclude, "We can augment experience design with first person performance methodologies found in Theatre, Dance and Somatic.… [P]articipants can learn to shift their own threshold of attention, awareness and body-state."[96]

Taking advantage of recent advances in motion-capture technology and using mathematical and statistical techniques, computer scientist Timothy Brick and psychologist Steven Boker developed methods to precisely record, codify, and characterize dancer movements. Their work led them to create "a set of tools" to analyze motion capture "in terms of how 'rhythmic' and 'regular' the dance may be … a new means of thinking about and making visible the patterns of synchrony and symmetry as they change across time."[97] Brick and Boker employ concepts such as translational, mirror, and temporal symmetry, as well as symmetries of velocity and acceleration, to characterize dancers' positions, displacements, and speed, and interactions among dancers over time. The formation and disruption of symmetry and synchronicity are of particular interest to them. The other statistical tools of correlation analysis allow them to visualize the overall architecture of a dance in new ways, taking into account its relation to the musical score and the relationships of dancers to each other.[98]

Exercises that use scientific concepts and technological devices to design dances make the creative process in choreography begin to resemble the experimental method of science. Choreography becomes movement research and the choreographer, an experimenter; creative dance ideas stem from an artist's mind as it encounters scientific notions and technological contraptions that motivate and leverage thought processes in ways akin to the formulation of hypotheses. Dance performances, enhanced by a host of technical devices that amplify the potential of human movement, could be viewed as experiments that test such hypotheses. However, one would have to acknowledge that choreographic researchers apply aesthetic, rather than epistemological, criteria to evaluate the results of their experiments.

Contemporary initiatives in computer choreography

As the panoply of electronic devices and software available becomes more varied, versatile, and accessible, computer choreography experiments now under way are likely to multiply. (See Box 5 on choreography apps for mobile phones and tablets.) The Choreographic Coding Lab associated with the Forsythe dance company, Adrienne Monbot and Claire Bardainne's combination of digital images and dance elements, and Wayne McGregor's use of his own DNA as a source of choreographic inspiration provide illustrations of the lively contemporary computer choreography scene.

The Choreographic Coding Lab (CCL) stems from an initiative derived from Motion Bank, a four-year research project of the Forsythe Company, whose 2009 joint project with Ohio State University was mentioned earlier. The format of the laboratory "offers unique opportunities of exchange and collaboration for digital media 'code savvy' artists who have an interest in translating aspects of choreography and dance into digital form and applying choreographic thinking to their own practice." Since 2013, CCL has organized labs in Frankfurt, Berlin, Melbourne, New York, Los Angeles, Auckland, Belo Horizonte, Amsterdam, and Nairobi. Scott deLahunta, mentioned earlier with regard to the development of the Choreographic Language Agent, is a member of the team leading the series of choreographic coding labs.[99]

Box 5: Choreography Apps for Mobile Devices

As attempts to improve dance notation and recording continued unabated, the ubiquity and accessibility of mobile phones and tablets provided ready-made tools for electronically imagining choreographic works. A project led by computer scientist Victor de Boer reviewed existing notation systems and then developed a smartphone-based simple tool, Interactive Dance Choreography Assistance, capable of storing seventy-eight ballet dance steps, fifty-seven modern dance steps, and thirty-one street dance steps. This program generates dance sequences in one of four modes, ranging from random generation to placing restrictions on syntactical relationships (what can follow what) through "ontology-based" rules.[100] An earlier survey conducted by de Boer and his colleagues of fifty-four Dutch choreographers had indicated that, to be useful, the tool must incorporate their diverse dance styles, add their existing choreographies to its archive, provide suggestions for variations, and be easy to use.

Passpartout, an application produced by publisher Patsy Tarr and designed by Abbott Miller, turns an iPad into an experimental stage. While the app can only store a limited number of dance movements, it does allow a large number of variations to be explored. Choreographers can record, mix, superimpose, rotate, and multiply segments of one-minute duration to create up to 13,000 permutations of dance sequences from which to select for the stage. The ease of use, low cost (US $0.99), and wide availability that the convergence between technology and choreography may be on the cusp of reaching wider audiences. According to Tarr, this app gives the user more insight into the choreographic process: "As you work with these layers, you start to see unison and symmetry and repetition." The idea was to allow the user to understand some of the "core concepts" of choreography by interacting with them.[101]

Choreographers Adrien Monbot and Claire Bardainne, who regularly perform with their dance group in various parts of the world, have developed several choreographic works combining digital, virtual, and real elements. Using customized electronic devices and computer programs, they design dances in which performers interact in real time with digital images that respond and adapt to their movements. Monbot, Bardainne, and their collaborators place the human body front and center as they, in their words, "adapt today's technological tools to create a timeless poetry through a visual language based on playing and enjoyment, which breeds imagination."[102] The author invites readers to view *Pixel*, Monbot and Bardainne's choreography developed in collaboration with dancer-choreographer Mourad Merzouki and staged in France, The Netherlands, Austria, and Slovenia in 2018.[103] A beautifully inventive and technologically challenging work, it seamlessly combines computer-controlled lighting effects and dancer movements.

Choreographer Wayne McGregor, whose earlier experiments with computer choreography were reviewed in preceding sections, engaged in a new exploration with his choreography *Autobiography*, premiered in London in October 2017.[104] McGregor used a complete sequence of his DNA as a "living archive" to provide data to an artificial intelligence algorithm, which creates sequences of dance moves never repeated from one performance to another. According to *Autobiography*'s dramaturge, Uzma Hameed,

> In this piece, book-ended by a fixed beginning and end, a number of choreographic events from the 23 volumes in the "life library" are selected and sequenced afresh for every performance by an algorithm based on McGregor's genetic code. For each iteration of the piece, the computer randomly selects a different section of code from the choreographer's genome to determine which material the audience will see, performed by which dancers and in what order. The system dictates that no individual sequence of code can be used more than once, so that no two performances can ever be alike.[105]

McGregor acknowledges that *Autobiography* poses difficulties for the dancers, who have to absorb and make meaning from dance steps learned shortly in advance of the performance. However, he calls the work "a little experiment that I think speaks directly to the idea of life-writing. Life unfolds, without our having control, and we have to deal with those instances. I think that can be a really beautiful thing."[106] A reviewer characterized the performance as "at once both incredibly rich and perversely sparse."[107]

It would be surprising if China's technological catch-up efforts did not attempt to explore the linkages between information technology and the arts. Chinese ventures in the field of computer choreography include experiments on the use of artificial intelligence and neural networks to create "a distributed and collaborative choreography scheme";[108] explorations of the feasibility of applying a "multimedia teaching system based on cloud computing" to the instruction of college dance majors;[109] and attempts to develop choreographic software using virtual technology to teach gymnastics.[110] These Chinese experiments have apparently remained at the prototype stage, and the lack of reference to other works, such as those reviewed in this essay, suggests they have been made without knowledge of previous attempts.

A recent book edited by professor of theater studies Maaike Bleeker gathers a number of important contributions to investigate the evolving relations between information technology and dance. Bleeker begins with the premise that "dance as a practice of doing, thinking, and transmitting movement has [the] most relevant expertise to offer" wherever the transmission of kinesthetic-motoric knowledge is concerned in newer and older media.[111] Examining twelve tools for transmission of movement across different media, Part I features contributions focusing on the work of choreographers such as Merce Cunningham, William Forsythe, and Wayne McGregor. Part II deals with broader issues, including digital archives, copyright law, and live-movement sampling.

Some of the recurring themes in the contributions to Bleeker's volume are how the intersection of physical and virtual spaces opens up new avenues for artistic creativity, how "dance's resistance to fixation … inspires alternative approaches to knowledge transmission," and how digital transformations bring to the forefront "the intimate connection between conceptions of what it means to know and the media we use to store and transmit knowledge."[112] According to Bleeker, the intrinsically time-bound nature of dance performance and its inherent ephemeral character make "dance … a practice of constant (re)generation. Dance exists only in the doing."[113]

For Bleeker "the fact that dance is continuously disappearing in the doing has been reason to argue that dance therefore cannot be adequately archived, or recorded, for it would become something other than performance."[*] From this perspective, using information technology to store and archive dance footage results in freezing and distorting the essential

[*] Maaike Bleeker, "What If This Were an Archive? Abstraction, Enactment and Human Implicatedness," in *Transmission in Motion: The Technologizing of Dance*, ed. Maaike Bleeker (London: Routledge, 2017), 200, 202. On this matter performance studies scholar Peggy Phelan argues that "performance's only life is in the present. Performance cannot be saved, recorded, documented, or otherwise participate in the circulation of representations of representations: once it does so, it becomes something other than performance" and "Performance in a strict ontological sense is nonreproductive." Peggy Phelan, *Unmarked: The Politics of Performance*, vol. 24 (Taylor and Francis e-Library, 2005), 146, 148.

character of dance as a performing art. Nonetheless, digital preservation of past experiments certainly offers the benefits of historical insight and provokes our imagination for future possibilities. Moreover, using the computer's capabilities to expand the possibilities of choreography and dance in live events can enhance and reaffirm the very nature of the art form.

Digital media make these issues ever more complicated, and interactive media—particularly those experiments/performances in which audiences participate—raise additional challenges for adequately capturing, storing, and disseminating choreographic works as well as ascribing authorship. With the introduction of random elements and audience input, which render each performance a radically unique and non-repeatable event, thorny implications for intellectual property rights emerge. In an increasingly digitally immersed economy, choreography and performance exist as knowledge in flux that challenges ascription of authorship, posing novel problems for artistic copyright.[114]

Philosopher Alva Noë's contribution in the last chapter of Bleeker's book offers reflections on the nature of choreography and its relation to perception, engagement, and consciousness. Noë poses the question, "If consciousness experience is itself … a kind of performance, something enacted and composed, an activity whereby we achieve presence, then what is the difference between conscious experience itself and the work of choreography?"[115] As he thinks through the implications of the answer, he waxes eloquent: "It is important to recognize that habit, unthinking engagement, skillful attunement with the world drawing on what we know and can do, is a good thing.… But it is also critical that we admit that because we are, in this sense, creatures of habit, we are also confined and constrained."[116] He continues:

> Choreography … makes this fundamental and indeed biological fact that we are governed by habit and situation, or by other forms of social control, its presupposition. And its aim, its project, is not to tune us up, or organize us better, but rather, to interrupt or disrupt … these inherited, invisible, unnoticed, familiar, conditioning forms of organizations. Choreography aims at disorganizing us. Choreography unveils the sometimes lovely, sometimes ugly ways in which we are always already organized and does so in a ways [*sic*] that must change us.… Choreography is important because, given that we are dancers, given that we are moving embodiments of organization and habit, we need to free ourselves from all that.[117]

Noë's philosophical speculations suggest that computers and information technology devices in choreography play the role of "disorganizers" and "disruptors" of entrenched habits of thought and practices, helping artists to free themselves from acquired or self-imposed constraints. His thoughts raise the question of the inherently embodied nature of human activities, including artistic creativity and scientific discovery, and highlight the counterpoint between our biological perceptual and motor systems on the one hand, and the products of our rational faculties on the other. The convergence of dance creation and performance with advances in information science and technology constitutes a privileged ground on which to explore deep philosophical implications of our embodied mind.[118]

Concluding remarks and further speculations

The imagination of those of us involved in the first computer choreography experiments in the 1960s, before the Apollo moon landing, was constrained by the state of computer science and technology at the time. Electronic processors were slow, limited, and quite expensive; mass storage devices required heavy investments and specially conditioned rooms, and visual displays were a luxury only the largest and well-equipped laboratories could afford. Leaps of ingenuity could only blurrily envisage what new information technology devices might emerge in the future, and the predictions of those who ventured along such speculative roads usually fell short of what actually happened.

Our paper on the computer choreography experiment carried out fifty years ago ends as follows:

> Looking at the future, let us imagine that the programs described here have been developed further. Taking the case of spatial movements for the moment, think what the choreographer would be able to do if he had a computer terminal with a visual screen (like the one described by Dr. Noll) and he wants to explore some ideas for using five dancers onstage, during five minutes, and with some other restrictions imagined by him. By typing a few instructions on the keyboard, the computer could be directed to generate an infinite number of dances which satisfy the restrictions specified by the choreographer, who can observe a few on the visual screen and then decide to take some of the patterns, discard others, and amalgamate different portions of dances. All the patterns would be submitted to him by means of the visual screen. It is still his decision whether to use any of the results and, if so, how to use them.[119]

As the contributions reviewed in this essay have shown, these anticipations fell woefully short of what a large number of choreographers, computer scientists, digital artists, and professionals from many different fields have achieved since the late 1960s; of what is happening now; and of what could be expected in the future. Even if we are still a long time away from truly reproducing human cognitive capabilities, recent advances in information technology have shown that it is possible to combine massive data, large storage capacities, and huge processing speeds with rules of inference and learning algorithms to emulate and even surpass our rational faculties in specifically limited ways.[120]

Beyond the use of various technical devices under the control of humans, advances in artificial intelligence have led to speculation that it may soon surpass human intelligence, not only in routine tasks but also in those that involve learning and creativity (Box 6). Technophilic advocates of the singularity hypothesis maintain that the aggregate of machine intelligence will be greater and more powerful than the total of human intelligence within a few decades, and that our species is entering a "transhumanist" stage of evolution.*

The implicit assumption is that artificial intelligence will improve by leaps and bounds, but that human intelligence will stagnate. Yet, it may be more sensible and fruitful to think that advances in the former will unlock new possibilities for the latter; that interactions between human and machine intelligence will bootstrap each other, opening new and extraordinary opportunities for joint advance. As fifty years of computer choreography show, human creativity can be nudged in novel and unexpected directions as researchers take advantage of the enormous capacity, speed, versatility, and learning capabilities of electronic devices and software.

Box 6: The (Spurious?) Threat of Artificial Intelligence Taking Over Human Reason and Creativity
Computer science pioneer Alan Turing argued that if machines could learn from experience, "there would be plenty to do in trying … to keep up to the standard set by the machines, for it seems probable that once the machine thinking method had started, it would not take long to outstrip our feeble powers.… At some stage therefore we should have to expect the machines to take control."† A similar and even starker assessment was made by I. G. Good, a Bletchley Park veteran, more than thirty years later:

> Let an ultraintelligent machine be defined as a machine that can far surpass all the intellectual activities of any man however clever. Since the design of machines is one of these intellectual activities, an ultraintelligent machine could design even better machines; there would then unquestionably be an "intelligence explosion," and the intelligence of man would be left far behind.[121]

In spite of the undeniable progress in artificial intelligence, speculations about the supremacy of artificial over human intelligence have a history of falling short of expectations.[122] Current developments point in

* Ray Kurzweil, *The Singularity Is Near: When Humans Transcend Biology* (New York: Penguin Books, 2006). For a wider exploration of man-machine interactions and the possibility of enhancing all human faculties through the use of advanced technologies, see Max More and Natasha Vita-More, eds., *The Transhumanist Reader: Classical and Contemporary Essays on the Science, Technology, and Philosophy of the Human Future* (Chichester, UK: Wiley-Blackwell, 2013). According to futurist Jennifer M. Gidley, in 1993, science fiction writer Vernon Vinge "predicted that we should have the technological means to create superhuman intelligence between 2005 and 2030, arguing this would end the human era." Jennifer M. Gidley, *The Future: A Very Short Introduction* (New York: Oxford University Press, 2017), 95.

† Alan Turing, "'Intelligent Machinery, a Heretical Theory.' Lecture given to '51 Society at Manchester. c. 1951," The Turing Digital Archive, accessed May 28, 2018, http://www.turingarchive.org/browse.php/B/20 About the same time, information technology pioneer Claude Shannon proposed designing a computer program to play chess using strategies that formulated criteria for strong positions and limited the amount of time the machine spent pursuing "pointless variations." Shannon's article also anticipated some of the features of current computer learning programs, for he suggested that data could be "supplied by a program and would be continually changed and kept up-to-date as the game progressed. The analytical data would be used to trigger various other programs depending on the particular nature of the position. . . . The machine obtains in this manner suggestions of plausible moves to investigate." Claude E. Shannon, "Programming a Computer for Playing Chess," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 41, no. 314 (March 1950): 273, https://doi.org/10.1080/14786445008521796.

the direction of artificial intelligence tools becoming quite sophisticated in a specific range of tasks, including business management,[123] music composition,[124] and even the codification and use of aesthetic criteria to generate fashion styles and works of art.[125] Computer hardware and software have also been used to create a musical theater show.*

Yet, skeptical voices suggest there will be always a role for humans to play. According to electrical engineering professor Michael Jordan, "Computing-based generation of sounds and images serves as a palette and creativity enhancer for artists. While services of this kind could conceivably involve high-level reasoning and thought, currently they don't—they mostly perform various kinds of string-matching and numerical operations that capture patterns that humans can make use of."[126] Psychologist Robert Epstein raises a more fundamental challenge to the idea that computers can surpass human intelligence—by focusing on our essentially embodied character: "Even if we had the ability to take a snapshot of all of the brain's 86 billion neurons and then to simulate the state of those neurons in a computer, that vast pattern would mean nothing outside the body of the brain that produced it."[127] The embodiment of human intelligence, mind, and self is eloquently examined in writer, broadcaster, and academic Laurence Scott's book on the impact of information technologies on our sense of place and the possibility of ubiquity.[128]

Half a century ago, the first experiments with computer choreography offered a glimpse of what would eventually become a rich and complex field of interaction between information technology, choreographic design, and dance performance, leveraged by a host of digital and analog electronic devices that changed how dances are created, performed, archived, and viewed. In parallel, the challenges of designing and performing computer choreography stimulated the ingenuity of information technology specialists, who, through hardware and software contraptions and even before taking into account dancer interplay with computer-controlled music, lighting, and objects onstage, devised innovative ways of apprehending the great complexity of human movement and spatial displacement.

Ada de Lovelace's metaphor of weaving algebraic patterns in the Analytical Engine can be updated in terms of modern computing: the weft of human movement imbricates with the warp of technological devices to create aesthetically pleasing works that rise above whatever any of these two sets of strands can do on their own.

What should we expect from the interaction between scientific progress and artistic endeavors during the next half-century? Current developments in information technology, artificial intelligence, and performing arts offer

* See Benjamin Till and Nathan Taylor, "Creative Differences with Android Lloyd Webber," interview by Rehman Tungekar, video in the show *Artificial Creativity*, January 15, 2017, https://www.ttbook.org/interview/creative-differences-android-lloyd-webber; "Beyond the Fence," YouTube video, 1:26, posted by Wingspan, November 30, 2015, https://www.youtube.com/watch?v=VZzI4sfCFjc; Rachel Sigee, "Beyond the Fence: Mamma Mia! Here's Android Lloyd Webber," *Evening Standard*, February 4, 2016, http://www.standard.co.uk/go/london/theatre/beyond-the-fence-mamma-mia-here-s-android-lloyd-webber-a3172846.html. A *New Scientist* reviewer curtly remarked, "As the curtain falls on Beyond the Fence, it's clear that the UK's musical theatre talents can sleep peacefully at night with little to fear from Android Lloyd Webber and his crowd of cybernetic pretenders." Stewart Pringle, "Beyond the Fence: How Computers Spawned a Musical," *New Scientist*, March 3, 2016, https://www.newscientist.com/article/2079483-beyond-the-fence-how-computers-spawned-a-musical/. *The Guardian*'s reviewer of *Beyond the Fence* was also quite dismissive: "Using elements that a computer has identified as key for musical success leads to a dated middle-of-the-road show full of pleasant middle-of-the-road songs, along with a risibly stereotypical scenario and characters." Lyn Gardner, "Beyond the Fence Review: Computer-Created Show Is Sweetly Bland," *The Guardian*, sec. Stage, February 28, 2016, http://www.theguardian.com/stage/2016/feb/28/beyond-the-fence-review-computer-created-musical-arts-theatre-london.

mere hints about what may happen. Information and communication technologies will continue to innovate the world of dance with video and holographic projections, motion-capture devices, artificial intelligence, and real-time processing. Hardware and software have been designed to control and coordinate music and video playbacks with dancer movements; to compose musical scores that accompany electronically enhanced dance routines; to use electronic sensors and artificial intelligence programs to capture, store, and process body movements; to record, process, and project dance movements—often with altered appearances—onto stage screens; to use sophisticated algorithms for learning about the stylistic preferences of a choreographer and to create new dances in their mold; to allow real and virtual dancers to interact with each other over time and distance; to intersperse holographic projections with real dancers onstage; to design dance games for mobile phones and tablets; to create interactive installations that allow choreographers, dancers, and audience members to perform and create new movement sequences; and to launch performance art multimedia experiments that combine music, dance, video, holograms, and robotic devices.[129]

Virtual, augmented, and mixed reality will expand the interaction space between information technologies and performing arts. Headsets and glasses have already been created to depict and project combinations of physically real objects with virtual images, which could allow audience members to alter at will and personalize stage performances by adding their chosen computer-generated avatars that interact with real dancers, video projections, and moving objects.[130]

Moreover, experiments with sensors that directly link brain neuronal activity with computers that amplify signals and instruct virtual images and real objects to move suggest it may eventually be possible "to think" or imagine a dance sequence and have it performed by combining virtual and physical entities with human dancers.[131] This would blur the distinctions between audience, choreographer, and performer, opening up new vistas for the co-creation of art works and for imagining new configurations of joint individual/collective artistic endeavors mediated by information technology.

Dance creation and performance are characterized by a counterpoint between physical movement expression and mental aesthetic appreciation. As Peggy Phelan put it, "Performance art usually occurs in the suspension between the 'real' physical matter of 'the performing body' and the psychic experience of what it is to be em-bodied."[132] Yet, the duality of real physical matter / psychic experience has become more complex and convoluted as a result of the swift emergence of cyberspace, virtual reality, and synthetic worlds. They have challenged the mind/matter dualism that had underpinned the modern worldview since the mid-seventeenth century and have created an intermediate realm of virtual entities less real than tangible physical ones, but more concrete than intangible concepts and ideas.[133] As this new realm is explored and inhabited, a mind/virtual/matter triad will set the scene for novel forms of expressing an enlarged range of human faculties. Dance and choreography are uniquely suited to lead the way in these explorations.

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FRANCISCO SAGASTI is a professor at the Pacífico Business School of the Universidad del Pacífico and a senior researcher emeritus at FORO Nacional Internacional, Lima, Peru. Trained in engineering, he holds a PhD in operations research and social systems sciences. He has been chairman of the Science and Technology Program at the Peruvian Prime Minister’s Office; a member of the Board of Governors of the Canadian International Development Research Center and other international organizations; founder of GRADE, a leading Peruvian think tank; chief of strategic planning at the World Bank; chairman of the

United Nations Advisory Committee on Science and Technology; a visiting professor at the Wharton School, the Instituto de Empresa, and the University for Peace; and a consultant to international public and private organizations. Publishing more than 120 papers and thirty books, Dr. Sagasti was honored with the Paul Hoffmann and the Robert K. Merton awards for his academic and policy contributions in the fields of science, technology, and development studies.