Dual-Use Technologies for Electronic Music Controllers: A Personal Perspective

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Abstract

Several well-known alternative musical controllers were inspired by sensor systems developed in other fields, often coming to their musical application via surprising routes. Correspondingly, work on electronic music controllers has relevance to other applications and broader research themes. In this article, I give a tour though several controller systems that I have been involved with over the past decade and outline their connections with other areas of inquiry.

1. FROM PHYSICS TO INSTRUMENTS

People devote an amazing amount of energy into developing new modes of musical expression. There's nothing quite like the satisfaction that one gleans after building and playing a new instrument, feeling its response, and hearing sounds that have never been produced before. Although most of the NIME audience is quite familiar with the technical literature in computer music (e.g., *Computer Music Journal*, *Journal of New Music Research*, *Leonardo Music Journal*, *Organized Sound*, etc.), the periodical *Experimental Musical Instruments*, and Bart Hopkins' books [1,2] give an excellent survey of a wider grassroots movement where artisans of all sorts bend their abilities into crafting new ways to create and shape sound. Indeed, people heralding from many daytime callings cross-fertilize all sorts of ideas and approaches from many fields into musical instruments.

When growing up, I was hardly immune to this muse; like many of my colleagues coming of age in the generation of consumer electronics, I essentially learned circuits by building various devices that made sounds, often buying old gear left over from the Boston area's extensive high-tech, military-industrial R&D at local surplus houses and hacking it to make music. Perhaps in my case, the expression got a little extreme in the 140-module homebrew patchable synthesizer that evolved in my basement during the 70's and early 80's [3]. In addition to being a source of unusual sounds, it is very much an intimate musical controller. Despite the drawbacks of being too closely wedded to the world of atoms, with a knob and patchcord on every signal, modular synthesizers provide a highly fine-grained, tangible, and parallel interface into sonic structure. Although it's a little rusty now, I'm not ready to surrender that axe to pasture…

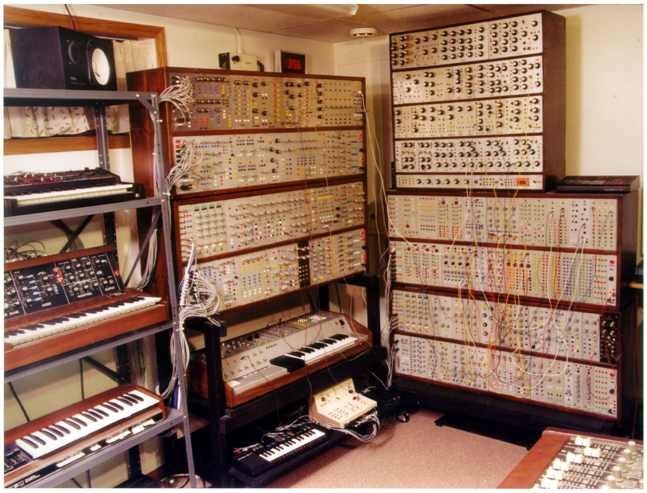

Figure 1: The homebuilt modular in my former basement

Since electronic music systems by definition rely on a fresh supply of ideas and technology to keep things current, instrument inventors and developers often tap the accessible edge of Moore's Law. Some fascinating stories can be found where this trend is pushed to its extremes, e.g., the initiative by North American Rockwell to push large-scale integrated circuit technology directly from the space program into musical instruments, resulting in the Allen Digital Organ, the world's first real-time digital wavetable synthesizer, which appeared on the market way back in 1971 [4,5]. This example illustrates how a mixture of different perspectives can lead to a disruption in an established field. Innovation seldom comes out of comfort; it often arises from a cultural clash [6], which frequently manifested testy circumstances as Allen engaged with Rockwell [5].

One would think that experimental high-energy physics would have little effect on electronic music controllers, but indeed it has, through several avenues. Since Bob Bowie had worked with Veljko Radeka's Instrumentation Group at Brookhaven National Laboratory, he was well aware of capacitive pickup electronics for cathode-strip drift chambers (standard charged-particle detectors) [7]. This proved to be the inspiration for the sensor system that he designed with Max Mathew's for the Radio Baton [8], one of today's best-known alternative controllers. As both Bob and Max knew Neil Gershenfeld through Bell Labs, these ideas propagated further into the Media Lab's cello bow controller [9] used in Tod Machover's Hyperstring performances [10]. At that time, I was also using capacitive sensing technology, but in high-energy physics applications at Draper Laboratory, this time using a stretched-wire to sense the precision alignment of drift chamber packages for the muon system of the proposed GEM detector at the Superconducting Supercollider (SSC) [11]. Upon joining the Media Lab in 1993, I pushed these technologies into a wireless violin bow tracker and a free-gesture controller for our *Sensor Chair* [9]. When designing the sensor suites for the *Brain Opera* performance interfaces [12], I again adapted technologies that we had developed earlier for aligning high-energy physics detectors. In particular, the *Digital Baton* [12,13] used an optical tracker based around a position-sensitive photodiode (PSD) that we had evaluated at Draper for GEM's optical straighness monitoring [14], and the laser rangefinder design that I turned into a hand tracker and musical interface for large projection walls [15,16] was inspired by a rangefinder that we had intended to use for dynamic detector surveying [17].

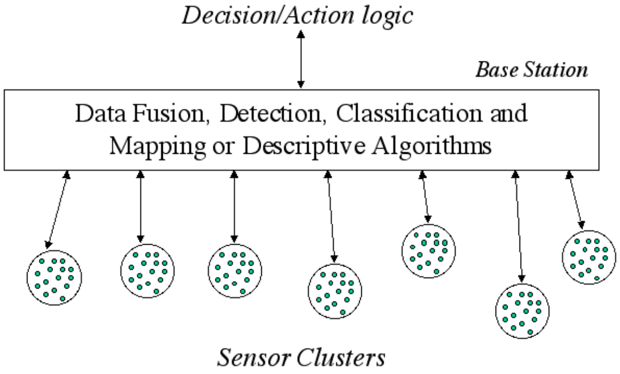

Figure 2: Wireless sensors in a star topology

2. HIGH-DENSITY WIRELESS SENSING

Although interfaces for electronic music face some very interesting research challenges on their own turf [18], this section will provide a few examples that illustrate how particular controller designs that we've pursued address broader research issues - essentially taking an opposite tack to the previous discussion. In particular, the goals of Ubiquitous Computing [19], which envisions sensors, processing, and communication moving into everyday objects and environments, form a good match to technical research in many avenues of musical controller design.

The sensor topology described in the next two sections is the centralized “star” with a heavy basestation, as portrayed in Figure 2. This topology is well suited, for example, to a wearable sensor array used in a dance performance, where one needs to rapidly acquire all information from every sensor cluster on the stage without the latency that would be incurred in a peer-peer network as shown in Figure 6.

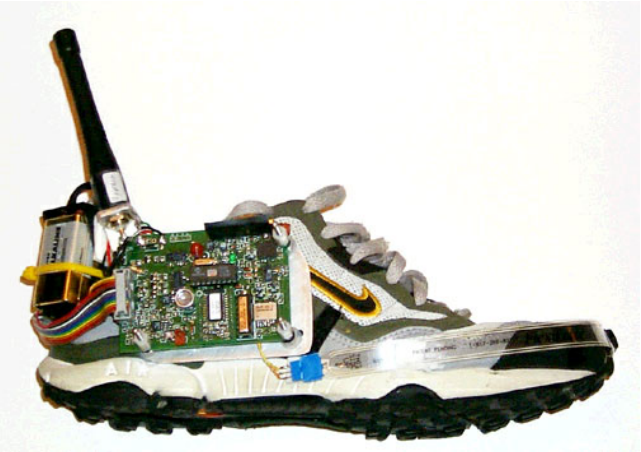

Figure 3: The final version of the *Expressive Footwear* shoe

When I first conceived of the *Expressive Footwear* project [20] in 1997, I wanted it to be a wireless sensor tour-de-force. Knowing nothing about dance, I threw every sensor that would fit and seemed even vaguely useful onto a dance sneaker, with a wireless datalink coming directly off the shoes. In the end, we put 16 diverse sensors on each shoe to measure many parameters of contact and free gesture together with position. We developed a series of such shoes between 1997 and 2000 [21].

As the first devices were deployed before compact sensor packages, such as the Motes [22,] became established, it was somewhat of a radical statement, an early case of what I call "sensing as commodity", partly inspired by the various dexterous glove interfaces developed at STEIM [23]. Traditional sensing applications have been based on measuring only parameters of direct relevance. When designing an artifact needing measurement, sensors are traditionally placed exactly where they’re needed to provide primarily the information required. Now that sensors are becoming so inexpensive and small, however, we can look at pursuing another, less stringent strategy that involves packing as many sensor measurements as possible into the object’s form factor. If there’s any suspicion that a measurement can be at all relevant, and if it can fit into the package constraints, just include it as a member of a large embedded sensor suite. This way, a host of multimodal sensor readings catch many features of activity and expression – instead of “sharpshooting” particular parameters of interest with explicit sensors, this approach catches a wide range of phenomena with multisensory “buckshot”, allowing one to reconstruct a variety of features and states by fusing the data in software. This allows an instrument designer or player to be more open to serendipity – the rich sensory stream produced by such a heavily instrumented controller captures many types of gesture, enabling a user to map an effective response to many types of activity and usage modalities that weren’t anticipated when the device was designed. In the case of the *Expressive Footwear*, this was indeed the case – after perfecting a compact circuit card to do such dense wireless sensing and survive on the foot of a dancer (a major challenge in itself [24]), the data stream was sufficiently rich to map expressive response onto many different styles of dance across the wide range of dancers that we worked with in this project.

We have since miniaturized this instrument package further, producing a device that we call the sensor "*Stack*" [25] that is composed of circuit cards roughly an inch and a quarter on a side. Mating at small connectors on their perimeter, different such cards can be vertically layered, allowing a designer to stack up a suite of sensing devices into a compact form factor, roughly the area of a large wrist watch. One card contains a 22 MIPs processor and RF transceiver; subsequent cards encapsulate different sensing modalities. At the moment, we have developed two sensor cards (a 3-axis inertial measurement unit [IMU], and a tactile input device that interfaces to pressure [FSR and piezo], bend, and capacitive sensors), and a sonar card is under development. Our current application of this platform is in medical biomotion diagnosis and therapy, where we're trying to use a heavily instrumented shoe to enable some of the function of a high-infrastructure gait laboratory at a hospital to be accommodated in a small doctor's office or home environment [26]. We are also planning to use this platform as a research tool to investigate state-driven processing and resource allocation in sensor nodes. As energy, computation, and communications bandwidth tend to be quite limited in battery-powered systems, sensor nodes have to take careful account of what sensors are used, what features are extracted, and what data is transmit [27]. Accordingly, appropriate processing at each node can extract a limited amount of local context in order to dynamically adjust this resource balance. Instead of blindly and wastefully dumping all measured bits all of the time, a more efficient sensor node will send only relevant features at appropriate times.

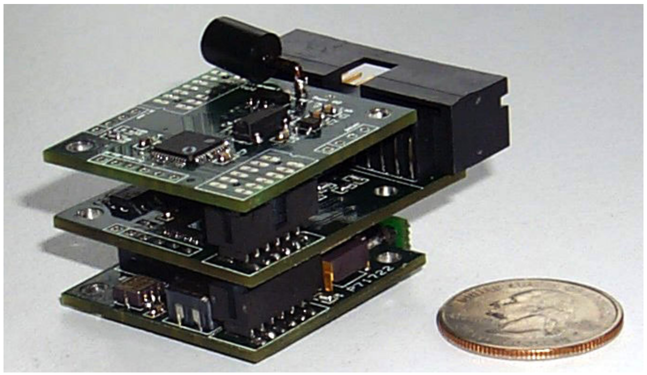

Figure 4: The currently working version of the *Sensor Stack*

In the near future, we intend to explore the application of our *Stack* in ensemble dance, where we instrument the hands and feet of a small troupe of dancers. By upgrading the 115 kbit/second RF transceiver that we're using to a 1-2 Mbit/second capacity and running a simple TDMA protocol, we anticipate being able to maintain a 100 Hz full state update from each node of this system for 4-5 dancers, effectively capturing many features of real-time dance performance. In addition to just building an architecture to acquire the data, this system will confront significant technical challenges in real-time data fusion in order to produce a prompt and relevant media response to the 300-500 parameters streaming in with each measurement update. There are likewise issues involved in content mapping here – we can no longer map our data directly at the sensor level, as is now conventional in MIDI mapping packages like MAX, since there's just too much dissimilar data streaming in to deal with by hand. Metavariables defined at a higher level, reflecting information relevant to the performer (perhaps inferred affect [28], synchronicity and deviation, energy, learned or entrained parameters, etc.), will need to be defined in order to effectively author content on top of these systems.

Figure 5: Low cost "jerk" sensor to instrument large crowd

3. FEATHERWEIGHT SENSORS

We have also been pushing another dimension in high density wireless sensing. Instead of making heavy nodes that each host many degrees of sensing freedom, we have developed a system that supports huge numbers of extremely lightweight nodes that each measure only one coarse parameter. This system has been targeted at interactive entertainment for large groups. Whereas Loren Carpenter's camera-driven Cinematrix [29] effectively and economically enables a large group to be instrumented with passive optical targets, kinetic musical expression, such as interactive dance, can have difficulty with the line-of-sight and lighting constraints that video-based approaches require. Accordingly, we have developed [30] an extremely compact wireless sensor that sends a narrow RF pulse out when it's jerked. As the active duty-cycle is so brief and since the circuit needs no complex components, a small, onboard watch battery lasts years of regular use. The device, manufactured in large quantity, is so inexpensive that it can be given out at sports games or dance raves as a party favor with the ticket, enabling participants to contribute some level of group control over interactive media. We have derived a set of real-time statistics from the data stream that indicate the level of activity, mean tempo, and significant events with many coincident hits, and have used these features to define parameters exploited by an interactive music system for MIT dance parties [31].

Although the results were intriguing, the area of interactive entertainment for large groups is still quite open – maintaining some degree of collective consonance and causal engagement with scores of participants is a difficult, if not impossible challenge [32].

These minimal wireless "featherweight" sensors have many applications in other areas. We will soon deploy them in "smart home" environments that monitor overall patterns of activity for elder care – a significant and growing problem, since so many seniors are living alone and unattended. Much more noninvasive than a camera or microphone, and potentially more reliable, these minimal sensor packages can be affixed to doors, furniture, cabinets, etc., where they will produce a wireless response to associated activity. By monitoring patterns evident in the wireless signals, deviations in habits can be detected, potentially indicating an evolving medical problem.

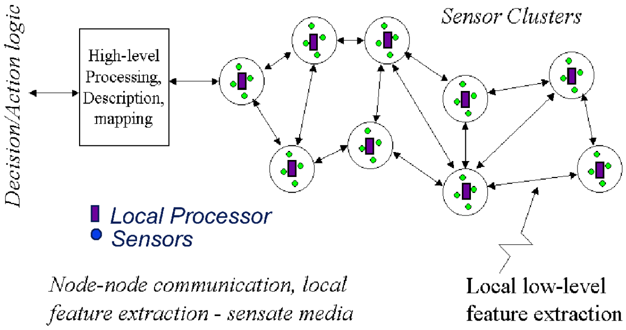

Figure 6: Dense peer-peer sensor network

4. ELECTRONIC SKINS

Another interesting frontier in dense, multimodal sensing is posed by the concept of sensate electronic skins. Applications abound in areas like robotics, telepresence, medical diagnostics, and prosthetics for very dense tactile arrays that approach the sensory capabilities of biological skin. Similarly, significant technical challenges are posed here in fabrication, microelectronics, and signal processing [33]. Today's tactile arrays (e.g., FSR [34] and fiber optic matrices [35], "smart skin" for aircraft wings [36], etc.) are all heavily multiplexed; a dedicated processor essentially scans all sensor cells and looks at each piece of data. Accordingly, these centralized systems have difficulty scaling up to large arrays because of the mass of wiring and data involved. In order to feasibly build such systems, processing must be blended smoothly into the sensing substrate. A rough inspiration can be taken from biology, where signals from tactile and other sensor receptors are combined and preprocessed in the nervous system, often before reaching the brain [37]. Hence, a possible manifestation of electronic skin involves a peer-peer, ad-hoc sensor network, much as has been proposed for battlefields, cities, and buildings, but shrunk down to a mm node spacing. In this scenario (Figure 6), a processor manages a group of local sensors (a mix of different types can be included to enable multimodal sensing – e.g., pressure, temperature, proximity, etc.), collecting and processing the resultant data, and communicating with its neighbors. When a stimulus occurs, the processors will cluster, characterize, and isolate it, thereupon routing the resultant high-level features out node-node to an external portal, suppressing the granular detail.

Such electronic skins could provide a very promising technology for advanced musical interfaces, as they possess both a high-resolution, multimodal, tactile sensing capability together with the possibility of local optical, tactile, and possibly acoustic display via actuators connected to each processor that are driven via a distributed control scheme. Musical performance or installation applications place tight requirements on the latency of response (depending on the instrument or interface, roughly 1-100 ms of delay can be tolerated), hence routing and internode communications protocols and topologies must be appropriately constrained.

Figure 7: 100 Pushpin nodes pushed into their substrate

Since the challenges here are considerable, we have developed a few hardware testbeds with which we can conduct experiments in dense sensor networks and begin to explore applications of such electronic skins. The first, "*Pushpin Computing*," [38] is composed of a large, sandwiched conductor/insulator power plane and an array of small processors with configurable communication and sensing/actuation capabilities (via a set of layered boards, as in the *Stack* described above). As the bottom layer of the Pushpin sports a pair of unequal-length insulated pins connected to the local power lines, Pushpins can be pushed into the power plane at any position, where they pull power from the conductors and establish communication (currently via IR) with their neighbors. Accordingly, the Pushpin system is highly configurable and has been used to test dynamic routing in sensor nets [39].

Another testbed now nearing completion is called the "*Trible*" ("Tactile Reactive Interface Based on Linked Elements") [40]. Shown in Figure 8, it is essentially a soccer ball tiled with 32 Circuit card "patches", each hosting a 22 MIPs processor and an array of up to 18 sensors, including pressure transducers, piezoelectric cantilevers bonded to fibrous "whiskers" that protrude from holes in the surface, microphones, temperature monitors, and light sensors. As each card also supports a small audio speaker, a vibrator, and an RGB LED, all nodes are capable of providing a direct, multimodal response. There is no central control in this system – the patches only talk to their neighbors, hence, as in Figure 6, they collectively process the sensor information and coordinate their local responses and/or route the processed features out to an external connection. Although we have yet to exploit its musical potential, with 516 channels of multimodal sensing and local actuation, the *Trible* promises to open up some interesting avenues of music control and distributed sound generation.

Figure 8: The *Trible*, before installation of its whiskers

Figure 9: A few assembled *Z-Tiles* under test

The last device in this category is a collaboration between the *Interaction Design Group* at the University of Limerick and the Media Lab's Responsive Environments Group called the "*Z-Tiles*" [41]. Partially shown in Figure 9, it is an array of interlocking, puzzle-shaped floor tiles, each of which hosts an array of five processors and a set of force-sensitive resistors, each roughly 3 cm in diameter. When the tiles are interlocked, a mating connector routes both power and digital data tile-tile, hence a sensor network is built up as the floor is assembled. Contrary to the previous sensate floors on which it was based (e.g., our *Magic Carpet* [16] and Limerick's *LiteFoot* [42]), which involved heavy cabling infrastructure that limited their span, the *Z-Tiles* are intrinsically scalable. Upon detecting pressure, neighboring tiles will communicate to isolate and characterize footsteps, then route the resulting features node-node to an attached computer that can provide an appropriate response. As the *Z-Tiles* were designed for interactive dance, the routing and processing routines need to be sufficiently prompt to avoid introducing excessive delay when passing messages across the maximum span of tiles in a given installation (and with a given amount of foot traffic). Although prototype tests of a half-dozen linked tiles have been completed, this system is currently under development. The resultant floor is planned to be used not just in entertainment, but also in "smart home" applications, where gait can be characterized and occupants tracked [43] throughout a responsive space.

Figure 10: The *Musical Trinkets* engaging a Crowd in Milan

5. OTHER EXAMPLES

Many other technologies that have made their way into the world at large have started from or been inspired by musical controllers. Force-sensitive resistors (FSR's), common components used for moderate-resolution pressure sensing in many applications, were perfected by a founder of Interlink [44] for sensing aftertouch on keyboard interfaces. The first conceptual implementation of spread-spectrum communication, posed by actress Hedi Lamarr and the composer of *Ballet Mechanique*, George Antheil, was based on the sequencing principles of a player piano [45].

I've been able to participate in pushing a few other musical controller designs into a range of applications. The swept-frequency tag reader that I designed for the *Musical Trinkets* installation [46] was inspired by Electronic Article Surveillance (anti-shoplifting) systems [47]. The *Trinkets* hardware is now evolving further into a 3D volumetric tracker for passive tags [48]. Although this has many potential applications in augmented and virtual reality (e.g., various control points on objects, fingers, etc. can be wirelessly tagged and tracked), this incarnation was inspired by the need to tag and precisely track the position of a tumor on a patient undergoing radiation therapy [49].

The *Sensor Chair* [9] is another controller that has had particular success outside of the musical realm. It began its life in 1994 as a transmit-mode capacitive sensing system to track free gesture at the arms and legs of a seated occupant, in this case, the magicians Penn and Teller, who used it to perform a mini-opera by Tod Machover together with a comedic séance [50]. Two attendees took special notice of this device in its performance debut at MIT's Kresge Auditorium that summer. One was the current agent for the Artist formerly known as Prince. After a convoluted series of events that is difficult to summarize, this connection culminated in one of the strangest musical interfaces that I've ever built, the *Sensor Mannequin* [9], an electric-field-sensing monstrosity probably stored somewhere deep in Paisley Park now. The other interested attendee at this event was from the North American division of NEC Automotive. He saw the *Sensor Chair* as a potential solution to a persistent problem in automotive safety, namely a sensor system that could determine whether or not to fire a car's airbag during a collision based on the status of the facing seat's occupant (several infants had recently been killed by airbag deployments when their car seat was not properly oriented). After adapting some of the innards of the *Sensor Chair* system, then prototyping and testing many layouts for sensate seats, they have moved to product with the Elesys *Seat Sentry* [51], now a feature on several cars in current production. Closing the circle, Motorola has recently released a 9-channel capacitive-sensing chip for this system, the MC33794 [52]. Originally inspired by the electronics in our chair, this device is a useful building block for musical controller builders wanting to work multichannel capacitive proximity sensing into their interaction portfolio.

Figure 11: Bono enjoying the Sensor Chair at MLE, Dublin

6. CONCLUSIONS

Electronic Music Controllers have absorbed technology, ideas, and innovators from many fields of inquiry and practice. Conversely, developments in musical interfaces have also contributed concepts, inspiration, and products to entirely different areas of application. The field is very much a melting pot, where artists and technologists hailing from many different backgrounds come together to exchange perspectives. Such environments are fertile incubators for new and disruptive concepts. Musical controllers also can provide excellent testbeds and challenges though which to explore and demonstrate ideas in areas like Ubiquitous Computing. Yes, at the end of the day in this field, the show is what counts the most. But along the way, interesting tributaries lead to territories that could never have been imagined beforehand. It's been a wild ride, and there's plenty of water still out there, so hold onto the hull and keep exploring!

7. ACKNOWLEDGEMENTS

I've touched on several projects in this paper that many people have contributed to, hence they all deserve acknowledgement. My past and present students in the Media Lab's *Responsive Environments Group* have been instrumental in most of these efforts; in particular, Kai-Yuh Hsiao, Ari Benbasat, Josh Lifton, Mike Broxton, Eric Hu, and Stacy Morris have been principal in many of the projects mentioned here. My early work on violin bows, sensor chairs, and the Brain Opera is what got me started in this area, thanks very much to a longtime collaboration with Tod Machover. Similarly, Neil Gershenfeld was the first to extend me the invitation to switch from my world of physics detectors and sonar systems at Draper Lab to the universe of bows and gesture controllers at the Media Lab (as this article entails, it's hard to keep both feet in any one place!). Several alumni were vital to some of the early projects noted here, particularly Ed Hammond, Pete Rice, and Josh Smith, who hung on through the *Sensor Chair* and *Brain Opera*. And, of course, many other students, faculty, and researchers at the Media Lab contributed to the efforts described here and are thanked for making the place the cutting edge that it is. I've delighted in exchanging ideas with my many colleagues doing musical interfaces at other institutes. In particular, Mikael Fernstrom from the University of Limerick has been a resource and friend in many projects beyond just the Z-Tiles. And, of course I give special thanks to Max Mathews for not only being a pioneer and inspiration to us all, but for also being perhaps the field's greatest boundary-breaker and cross-fertilizer as he brought disparate talent and strong ideas together to push music deep into the future.

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