Revolutionary physics in reactionary Argentina

Wolfgang Bietenholz and Lilian Prado

In a time of political turmoil, two Argentine physicists developed a key technique for making sense of quantum field theories.

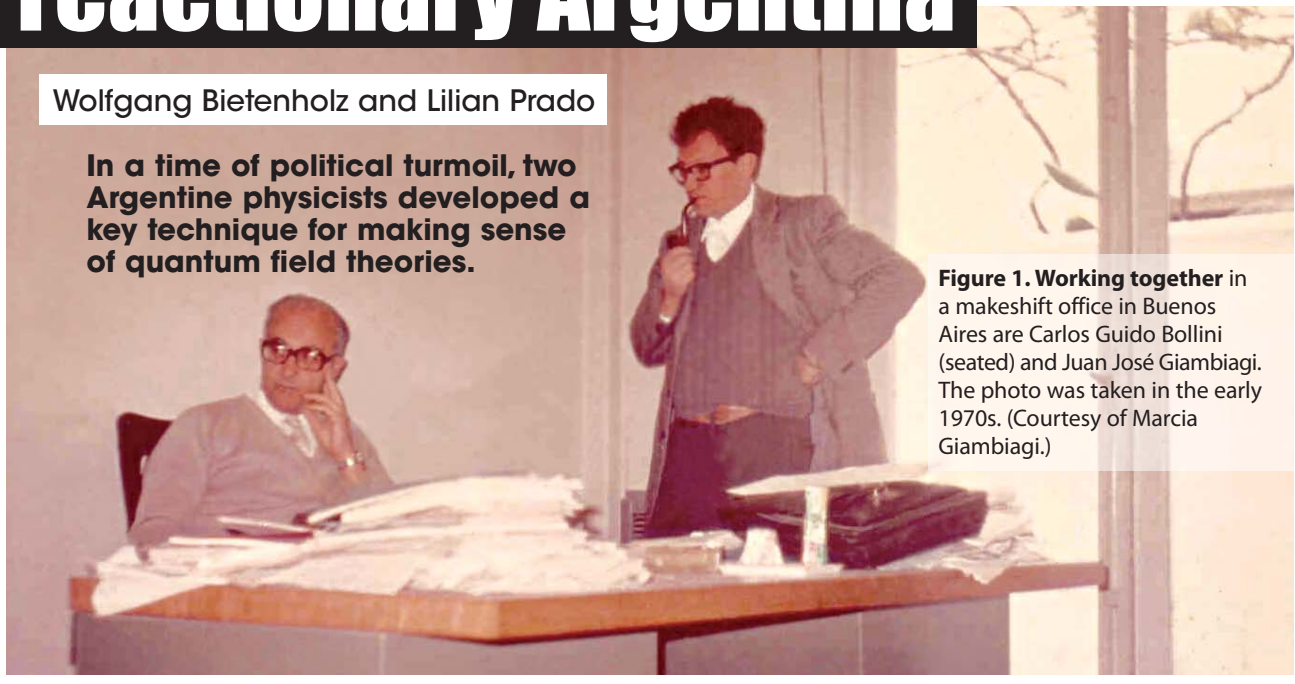

Figure 1. Working together in a makeshift office in Buenos Aires are Carlos Guido Bollini (seated) and Juan José Giambiagi. The photo was taken in the early 1970s. (Courtesy of Marcia Giambiagi.)

The highly successful standard model of particle physics is formulated as a quantum field theory. Analytic calculations in the QFT framework are typically realized as a perturbation expansion, in which one starts from a theory of free particles and systematically computes corrections in increasing powers of an interaction parameter. Straightforward application of the algorithm yields numerous divergent terms; to make sense of them, one needs to regularize them in a subtle way that ultimately allows for a physical limit to be taken.

In 1971 a new method—dimensional regularization—was proposed; within a year it was fully established. Dimensional regularization was the essential tool for the revolution in theoretical particle physics in the early 1970s—a revolution that led to the standard model. Many physicists, though, are unaware that the origin of the regularization scheme was in Latin America, specifically in La Plata, Argentina. The story of the Argentine contribution is a fascinating one. We will tell it with a minimum of technical detail, though for interested readers we sketch the theoretical background in boxes 1 and 2.

End of a golden age

For much of the 20th century, Argentine universities benefited from their status as autonomous institutions. Autonomy meant that the universities were independent of external powers—in particular the government and the Catholic Church—when making decisions on issues related to academics, organization, finance, and more. Such decisions were usually based on the recommendations of an elected council comprising mostly professors but also other university employees and students. The events leading to the autonomy system began in earnest in 1918, two years after democracy was established in Argentina, when students at the National University of Córdoba demanded educational reforms. Later that year those reforms were adopted at Córdoba, and the concepts advanced by the university students soon spread all over the country, notably to the University of Buenos Aires (UBA), and to numerous other Latin American countries.

The autonomy system did not just increase the academic quality of the universities. It also boosted cultural freedom and creativity, and the benefits accrued to the university had a corresponding impact in the larger society. Thanks in part to university autonomy, Argentina in the 1950s and early 1960s enjoyed a golden age in many features of its culture. One was science, particularly at the physics department at UBA. A key person responsible for that remarkable development was a young professor named Juan José Giambiagi,[1] who was the head of the department from 1957 to 1966. Under his direction the department expanded, gained worldwide reputation, and attracted highly motivated students. Among them was Miguel Virasoro, a pioneer in string theory perhaps best known for the so-called Virasoro algebra used in string theory and for

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directing the International Centre for Theoretical Physics in Trieste, Italy, during 1995–2002.

In the 1960s Giambiagi started a long-term collaboration with Carlos Guido Bollini; the two of them are shown together in figure 1. Both were mathematically oriented theoretical physicists at UBA (Bollini also had a background in nuclear energy), and both had established international contacts during stays in England. They were especially interested in particle-physics applications of mathematical objects called distributions or generalized functions. Unlike ordinary functions, which assign a value to a given argument, generalized functions are only well defined under an integral; by far the best-known example is the Dirac δ function. The two colleagues thoroughly studied the books by Russian mathematicians Israel Gelfand and Georgiy Shilov, especially the first volume of their five-volume work *Generalized Functions* (Academic Press, 1964). Even in his old age, Giambiagi called that book his bible; he knew many formulae and their derivations by heart and remained convinced that distributions had great potential as a tool for physicists.

On 28 June 1966, a coup d'état in Argentina brought General Juan Carlos Onganía to power; having overthrown President Arturo Illia, he declared his ambition to rule for 40 years. Once in power, Onganía immediately dissolved the parliament and forbade activities of political parties. His next target was the universities: He canceled university autonomy, dissolved the elected councils integral to the decision-making process, and banned student centers. University control was given to the deans and rectors, who were subject to the Ministry of Education. The goal was to cleanse the universities of "subversives," as defined by the military regime; avant-garde art, for example, was declared immoral.[2]

The rector of UBA, Hilario Fernández Long, expressed his opposition to the military dictatorship and its violation of the constitution. The regime gave him and the deans 48 hours to accept the new rules. That evening, the university council and additional professors met at a building in the School of Exact and Natural Sciences, which included the departments of biology, geology, chemistry, mathematics, and physics. The expanded council and dean Rolando García firmly agreed to reject the new rules and to spend the night in the building. The federal police invaded the building that night—before the 48-hour deadline had expired—beat up everybody they found, and destroyed laboratories and libraries, even though the university personnel put up no resistance other than to lock the doors. That event is known as *la noche de los bastones largos*, or the night of the long billy clubs. Four hundred professors and students were arrested; some of them are shown in figure 2. Among the arrested was Warren Ambrose, an MIT professor of mathematics and visiting professor at UBA. He wrote an account of the invasion in a letter to the *New York Times*, published on 3 August under the title "Short minds, long sticks."[3]

The international physics community reacted promptly. A total of 192 renowned physicists,

Box 1. Dimensional regularization

In quantum field theory (QFT), free fields can be handled exactly. For interacting fields, perturbation theory leads to an expansion in powers of interaction terms. The computational procedure dictated by perturbative QFT seems straightforward, but in practice it generates integrals such as

$$\int \frac{d^4p}{(2\pi)^4}\,\frac{1}{p^2+m^2}\,, \tag{1}$$

which diverges as the momentum p gets large.

To handle the infinities that a QFT presents, one needs to regularize the integrals—that is, render them finite while preserving the symmetries of the theory or allowing those symmetries to be restored in the final limit in which the regulator is removed. A conceptually simple approach to regularization is to introduce a momentum cutoff Λ to the integrals. But in quantum electrodynamics among other QFTs, such a cutoff will not preserve the crucial symmetries.

A better approach is dimensional regularization, in which one begins with an integral in d rather than four dimensions. For example:

$$\begin{aligned}\int \frac{d^dp}{(2\pi)^d}\,\frac{1}{p^2+m^2} &= \int \frac{d^dp}{(2\pi)^d}\int_0^\infty dt\; e^{-t(p^2+m^2)}\\ &= \frac{1}{(4\pi)^{d/2}}\int_0^\infty dt\; t^{-d/2}\,e^{-tm^2}\\ &= \frac{m^{d-2}}{(4\pi)^{d/2}}\Gamma(1-d/2).\end{aligned} \tag{2}$$

Here the Γ function—the famous generalization of a factorial—is given by

$$\Gamma(z) = \int_0^\infty d\tau\;\tau^{z-1}\,e^{-\tau}. \tag{3}$$

It is well defined for all complex z with a positive real part, and integration by parts gives

$$\Gamma(z-1) = \frac{1}{z-1}\Gamma(z). \tag{4}$$

This recursion allows the Γ function to be analytically continued over the entire complex plane, except for zero and the negative integers. In particular, in $d = 4+\varepsilon$ dimensions, the Γ function in equation (2) becomes

$$\Gamma\left(-1-\frac{\varepsilon}{2}\right) = \frac{2}{\varepsilon} + \gamma - 1 + O(\varepsilon), \tag{5}$$

where $\gamma = 0.577\ldots$ is Euler's constant.

In the dimensionally regularized integral, the divergence presented by the perturbation prescription is isolated in the $1/\varepsilon$ term, which, of course, blows up when ε is taken to zero—that is, when one returns to four dimensions. According to the computational rules for QFTs, those divergences formally contribute to physical quantities, such as the mass of a particle. However, physical quantities also receive contributions governed by so-called bare parameters built into QFTs. For a physical quantity such as mass to remain finite as ε goes to zero, the appropriate bare parameters must diverge in a way that cancels out the $1/\varepsilon$ term arising from the regularization.

Does a given QFT contain enough bare parameters to soak up all the problematic potential divergences and safely allow the regulator (here ε) to approach zero? And will the procedure for canceling divergences preserve the theory's crucial symmetries? A theory that can answer yes to both questions is said to be renormalizable. In practice, establishing that a theory is renormalizable can be a very difficult business indeed.

including six Nobel laureates and eight more who would later receive Nobels, signed a public letter of protest sent to Onganía. The regime ignored that letter, but four ex-UBA physics professors—among them Bollini and Giambiagi—published in the newspaper *La Nación* a Spanish translation, which they felt compelled to bring to the public's attention. The online version of this article includes the protest letter and an English translation of the preamble by the four professors, in which they point out that 69 of the 75 professors and researchers of the School of Exact and Natural Sciences had resigned because of the government's intervention.

Too strange to publish

La noche de los bastones largos and its aftermath disrupted academic activities in Argentina for several decades. Due to that invasion and the subsequent repression, all deans at UBA resigned, as did 1400–1500 professors around the country; about 300 of the best scientists, Virasoro among them, left Argentina altogether.[3] The excellent physics department at UBA fell into ruin. Bollini, Giambiagi, and other theorists continued their work away from the UBA campus, in a two-room apartment in the Colegiales neighborhood of Buenos Aires. (Figure 1 shows Bollini and Giambiagi working together in one of the rooms.) In an ironic salute to the general whose actions forced the move from UBA, the theorists named their apartment the Juan Carlos Onganía Institute.

In time, Bollini and Giambiagi moved from Buenos Aires southeast to the town of La Plata, where they worked at a smaller university from 1968 to 1976. Working conditions were not particularly good. For instance, the physics department did not even provide offices for them; instead, they installed themselves in the math department. Economic crises and political repression were ongoing, and communication with the international physics community was limited. Physics journals arrived up to 6 months late.

Despite the difficult conditions, the La Plata years turned out to be Bollini and Giambiagi's most productive period. Gifted students from UBA joined them, including Fidel Schaposnik, now a prominent leader in Argentinian high-energy physics. In 1971 Bollini and Giambiagi came up with a new idea for how to make sense of the divergent integrals that arise in perturbative QFT. Their approach, briefly described in box 1, surprised many physicists: They calculated in $d = 4 + \varepsilon$ dimensions and took the limit $\varepsilon \to 0$ only at the very end.

Their new method—dimensional regularization—was related to a technique called analytic regularization that they had developed years earlier with Giambiagi's PhD adviser, Alberto Domínguez. But dimensional regularization was more powerful. Bollini and Giambiagi first applied their technique to spinless particles, and in November 1971 they submitted an article to the well-respected journal *Physics Letters B*, published by the Dutch house Elsevier. However, the editors and referees found the new approach too strange and blocked its publication. We were not able to retrieve a copy of the referee report, but apparently it advised the authors to stop wasting their time[4] and return to work in $d = 4$.

Following that rejection, Bollini and Giambiagi wrote another article presenting their new approach. The second paper was more extensive and included applications to quantum electrodynamics; in particular, they demonstrated that dimensional regularization preserves the gauge invariance of quantum electrodynamics, a crucial criterion for a regularization scheme (see box 2 for a review of gauge symmetry). They sent the new work to the Italian journal *Il Nuovo Cimento B*, where it arrived

Box 2. Gauge symmetry in QFT

By 1970 quantum field theory (QFT) had been established as the appropriate formalism for explicating the physics of elementary particles. The acceptance of QFT resulted from the success of quantum electrodynamics (QED), the field theory describing the interactions of electrically charged particles and photons. QED inherits a symmetry, called a gauge symmetry, from classical electrodynamics. In the classical theory, physics is unchanged if the scalar potential V and vector potential $\mathbf{A}$ undergo the gauge transformation $V \to V - \partial\varphi/\partial t$, $\mathbf{A} \to \mathbf{A} + \boldsymbol{\nabla}\varphi$. In QED, the four components of the electromagnetic potential field describing the photon undergo that same transformation, but the fields corresponding to the charged particles also undergo a coordinated transformation, multiplication by a phase factor $e^{iq\varphi}$, where q is the electric charge of the particle. Note that $\varphi(t,\mathbf{x})$ can vary with time and position; for that reason the gauge symmetry is referred to as local. Also, one can apply multiple gauge transformations, and the resulting composite transformation will not depend on the order in which they are applied. Transformations with that property are called abelian; rotations in the plane are a familiar example.

The gauge transformations needed to unify the weak interaction, responsible for nuclear decay, and the electromagnetic interaction have a more complicated structure than those of QED. In particular, order matters; those non-abelian transformations are analogous to three-dimensional rotations. Until 1970, QFTs based on non-abelian gauge transformations seemed to be non-renormalizable. That is to say, the schemes that successfully handled the divergences arising in QED failed for such theories (called Yang–Mills theories after originators C. N. Yang and Robert Mills), and no one knew how to start from those theories and extract finite, predictive results.

However, in 1971 Gerard 't Hooft, a brilliant PhD student at Utrecht University, formulated a procedure for how to make sense out of Yang–Mills theories, given a regularization scheme, such as the dimensional regularization described in box 1, that preserves the invariance of the theory under gauge transformations.[9,15] Meanwhile, physicists were trying to devise such regularization techniques in many countries worldwide, including Argentina.

Figure 2. Argentine federal police invaded the University of Buenos Aires, administering beatings and arrests, on *la noche de los bastones largos* (the night of the long billy clubs), 29 July 1966. The event emphatically marked the end of university autonomy in Argentina.

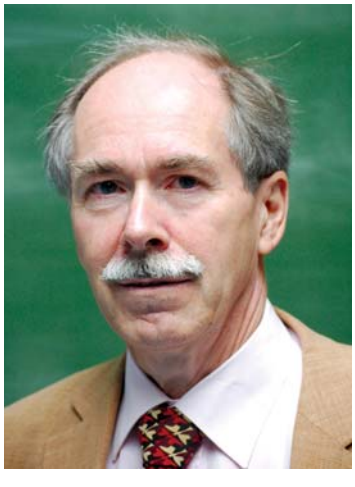
on 18 February 1972. It was accepted, but it was not published until 11 November.[5] Meanwhile, preprints of both papers had been sent to European and North American libraries. Giambiagi was sure that they were available in the CERN library, for instance, so it seems plausible that theorists worrying about regularization would have known about that work.

On 21 February, three days after Bollini and Giambiagi's manuscript arrived at *Il Nuovo Cimento*, Gerard 't Hooft at Utrecht University in the Netherlands and his PhD adviser, Martinus Veltman, submitted an article describing dimensional regularization to *Nuclear Physics B*, another Elsevier journal. The 't Hooft and Veltman work was more extensive, and it contained applications to so-called Yang–Mills theories, such as the one that unifies the weak and electromagnetic interactions. Importantly, 't Hooft and Veltman showed that such theories could be successfully renormalized via dimensional regularization—a technical way of saying that finite physical quantities can be derived despite the divergent integrals that arise in the QFT. (Figure 3 shows the two scientists, who received the 1999 Nobel Prize in Physics.) Their article[6] was published swiftly, on 1 July. About a month later, the original work by Bollini and Giambiagi finally appeared[7] in *Physics Letters B*.

The 't Hooft and Veltman paper was the first of the three dimensional-regularization works to be published, due to its swift editorial processing, even though it was the last to be submitted. It is generally viewed as an independent accomplishment, realized a little later than the work from Argentina but much more comprehensive. It is noteworthy, however, that 't Hooft and Veltman quoted the preprint from La Plata and that Veltman was a member of the advisory editorial board of *Physics Letters B* when Bollini and Giambiagi submitted their first paper. Nevertheless, Veltman later wrote that he had seen the preprints from La Plata for the first time in March 1972, when he received them in a letter from Bollini and Giambiagi. At the time, he was working on the revision of his article with 't Hooft.[8] He further claimed that 't Hooft and he had expressed the idea of dimensional regularization previously, citing section 5 from an earlier work of 't Hooft on renormalization.[9] However, that section addressed only an extension to five dimensions.

Dimensional regularization precipitated a revolution in particle physics. We've already noted that 't Hooft and Veltman used it to show how to make sense of the unified electroweak theory. In 1973 scientists at CERN observed a key new phenomenon, known in the field as neutral weak current, that had been predicted by that unified model; later researchers found the theory's three massive force-carrying gauge bosons.

Also in 1973, Harald Fritzsch, Murray Gell-Mann, and Heinrich Leutwyler described the "several advantages" of another Yang–Mills theory: quantum chromodynamics, with its quarks and force-carrying gluons.[10] The so-called asymptotic freedom of the theory was understood in the same year, an insight that led to a perfectly consistent picture of the hadronic world of protons, neutrons, and other particles built from quarks and gluons. Thus the standard model of particle physics was established. In July 2012 two collaborations working at CERN found the final ingredient predicted by the standard model, the Higgs particle. (For additional history and details, see PHYSICS TODAY, December 2004,



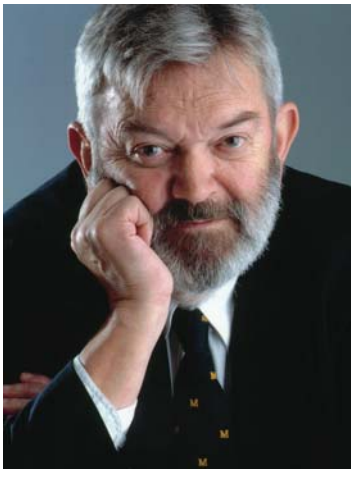


Figure 3. Dutch theorists Gerard 't Hooft (left) and Martinus Veltman wrote a paper on dimensional regularization with a more extensive treatment than in the work by Carlos Guido Bollini and Juan José Giambiagi. The 't Hooft and Veltman paper was published just a month earlier but Bollini and Giambiagi were actually the first to submit to a journal. (Photo of 't Hooft by Wammes Waggel; Veltman photo by Sjaak Ramaliers, courtesy of the AIP Emilio Segrè Visual Archives, W. F. Meggers Gallery of Nobel Laureates.)

Figure 4. General Luciano Menéndez (right) inspects the troops of Operation Independence in Tucumán, Argentina, in 1975. Menéndez helped lead the coup d'état that ousted Isabel Perón in March 1976. By the end of 1997, physicists Juan José Giambiagi and Carlos Guido Bollini exiled themselves from their homeland.

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Escape to Brazil

As the elements of the standard model were coming into place, the people of Argentina were experiencing hard times. In 1973 Giambiagi was interrogated by the federal police and accused of being part of a Jewish or communist conspiracy. As evidence, the police cited the relatively large number of Jewish physicists who had signed the petition sent to Onganía in 1966. However, Giambiagi successfully countered those accusations. He mentioned, for instance, the considerable funds received from the US Ford Foundation, which he had arranged when he was still head of the physics department at UBA. He then asked the authorities if they really expected that the Ford Foundation would sponsor a communist conspiracy.

The national situation got even worse in March 1976: Argentina suffered another military coup, this time against Isabel Perón. The new military regime instituted a national campaign—the infamous Dirty War—against political dissidents and other left-wingers. General Luciano Menéndez (seen in figure 4), one of the military leaders, announced "We are going to have to kill 50,000 people: 25,000 subversives, 20,000 sympathizers, and we will make 5,000 mistakes."[11] In April he ordered the burning of books by such authors as Gabriel García Márquez and Pablo Neruda. In June 1976 US Secretary of State Henry Kissinger visited Argentina and signaled to the generals there that the US government supported them.[12]

To intimidate the population, the military regime made frequent arrests based on unsubstantiated accusations. Soldiers would break into and steal from houses or beat up randomly selected people on the street. During the military rule from 1976 to 1983, those who seemed suspicious to the regime could suddenly "disappear"—that is, be taken to secret prisons, tortured, and killed. The number of victims from that period is estimated to be 10 000–30 000.

The military leaders generally viewed intellectual activities with distrust. They dispatched spies to systematically infiltrate the universities and identify students or professors with critical views; those so identified were in danger of disappearing. Even using such terms as "bourgeoisie" was sufficient to arouse suspicion. The University of La Plata was among the institutions affected. In 1976 Giambiagi was again interrogated by the federal police. The incident must have been very aggressive and frightening; in any case, soon afterward he and his family decided to flee Argentina and escaped to Rio de Janeiro, Brazil. They traveled by land to avoid airport controls. In the following year, Bollini's home was invaded by federal police, who threatened his family as they searched for evidence that he was involved with a communist conspiracy. Finding none, they contented themselves with stealing items from the house. The Bollini family, too, decided to escape to Rio de Janeiro.

Before long, the two physicists were working at the Centro Brasileiro de Pesquisas Físicas (CBPF; Brazilian Center for Research in Physics). Giambiagi was the head of the center's particle-physics department from 1978 to 1985. One year after that term ended, he became director of the Centro Latino-Americano de Física (CLAF), which he had founded back in 1960 with two prominent colleagues: José Leite Lopes from Brazil and Marcos Moshinsky from Mexico. Giambiagi encouraged interested young scientists at CLAF to address subjects of practical relevance, such as energy resources and climate.

Brazil had its own right-wing military regime from 1964 to 1985, though it was somewhat less cruel than those in Argentina, Chile, and Uruguay. It tolerated Bollini and Giambiagi, but other scientists in Brazil did get in trouble for their alleged involvement with communist conspiracies. In particular, Leite Lopes, perhaps Brazil's most important theoretical physicist, was forced to vacate his position in 1969. He left Brazil for France, where he became a professor at the Louis Pasteur University in Strasbourg; he returned to Brazil in 1986.

One of us (Bietenholz) had the opportunity to visit CBPF in the 1993–94 academic year, when Leite Lopes and Giambiagi were there. Both were still lively and eager to discuss almost anything; Giambiagi was still active in research. He and Bietenholz wrote a paper together, which was one of Bietenholz's first and, unfortunately, one of Giambiagi's last. He passed away in Rio de Janeiro in 1996. That year the physics department at UBA was named the Juan José Giambiagi Department of Physics. The International Centre for Theoretical Physics honored the scientist's memory with a Giambiagi lecture hall, dedicated in 2001. Bollini moved back to Argentina in 1985 after the military regime ended and democracy was reestablished. He returned to the University of La Plata and worked there as a physics professor from 1985 until his retirement in 1995. He passed away in 2009.

Little mention in Stockholm

In 1999 't Hooft and Veltman deservedly received the Nobel Prize in Physics "for elucidating the quantum structure of electroweak interactions in

physics." The Royal Swedish Academy of Science's advanced-information article mentions the names of 15 other researchers who had done related work but does not include the Argentine contribution.[13] The four papers cited in that document are all by 't Hooft, Veltman, or the two laureates together. The Nobel lecture by Veltman includes a side remark about "the independent work of Bollini and Giambiagi," though that work is not included among the more than 50 papers in his reference list.[14]

As of this writing, the dimensional-regularization paper by 't Hooft and Veltman[6] has close to 3100 citations, according to INSPIRE, a high-energy physics literature database. Bollini and Giambiagi's *Physics Letters B* paper has a bit more than 300 citations, and the *Nuovo Cimento B* work just over 600. The citations to the La Plata work are considerable, but they are not proportionate to the immense impact of dimensional regularization. That technique, now routinely explained in textbooks, has become the standard method for perturbative calculations in QFT. And 40 years ago, it was an essential tool that enabled the construction of the standard model of particle physics.

It is a pleasure to thank Ernesto Bollini, Marcia Giambiagi, José Helayël-Neto, Octavio Obregón, Mario Rocca, and Fidel Schaposnik for helpful communications.

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