Quantum Impedance Networks of Wavefunction Interactions

A Lost Organizing Principle in the History of Physics

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Abstract

A companion essay traced the loss of an explicit geometric representation of the vacuum wavefunction from quantum physics. The present essay considers a second lost organizing principle: impedance matching.

Long before quantum mechanics, impedance matching had become a general means of understanding amplitude and phase in the transmission of energy between interacting mechanical and electromagnetic systems. Quantum mechanics retained the associated phenomena—phase, amplitude, scattering, reflection, transmission, resonance, tunneling—but did not organize them in terms of impedance matching.

The principle was never entirely absent. From the late 1950s through the mid-1960s, works by James Bjorken and Richard Feynman brought quantum systems, electrical networks, and impedance matching remarkably close together without producing a general synthesis.

In 1975 an independent route unknowingly returned to the problem through a mechanical quantity whose significance would not be recognized for another thirty-five years. Subsequent developments connected the resulting quantum impedance networks with the fine-structure constant, particle phenomenology, the Planck scale, and geometric algebra. The independently developed impedance and geometric descriptions were ultimately found to converge: geometry identifies the possible modes of the wavefunction, while impedance matching provides a relational description of their interaction.

The history illustrates how successful mathematical representations can preserve physical phenomena while obscuring alternative organizing principles.

1 Introduction

Physics is shaped not only by the interplay of theory and experiment, but also by the mathematical tools through which they are expressed. A successful representation can reveal relationships that were previously obscure. It can also conceal relationships that remain fully present in the physics.

A companion essay[1] examined one such loss in the development of quantum mechanics: the loss of an explicit geometric representation of the vacuum wavefunction. The geometric structure remained present in the algebra, but became less visible in the matrix representations through which quantum mechanics developed. The alternative considered in the companion essay began with the geometric wavefunction[2], determined the modes it permits, and then asked how those modes become physically manifested.

The present essay concerns a second organizing principle that followed a surprisingly similar path. Long before quantum mechanics, impedance matching had become a general principle governing the transfer of energy between interacting systems[3, 4]. Mechanical, electromagnetic, and optical realizations differ, but the underlying relation is the same. Impedance matching governs amplitude and phase of the flow of energy between interacting systems.

Quantum mechanics retained virtually all of the phenomena associated with this principle. Quantum waves reflect and transmit, tunnel, form standing waves and bound states, undergo resonant transmission, and scatter. Quantum field theory organizes interactions through complex amplitudes and phases. Yet impedance matching did not become a general organizing principle of quantum physics.

How this happened is the subject of the present essay. The history is not one of simple absence. Impedance repeatedly approached quantum theory, particularly in works of both James Bjorken and Richard Feynman. But the pieces were not assembled. An independent route, beginning far from quantum theory, eventually returned to mechanical impedance and to networks of quantized wavefunction interactions.

2 Impedance Matching Before Quantum Mechanics

Impedance did not enter physics as a single discovery. It emerged as physicists and engineers learned to describe oscillatory systems and the transmission of energy between them.

Electrical resistance supplied the elementary form of Ohm's law,

$$R = \frac{V}{I}. \tag{1}$$

With alternating currents, inductance and capacitance introduced energy storage and phase. The corresponding quantity became complex,

$$Z = R + iX, \tag{2}$$

relating amplitude and phase of voltage and current.

The development of transmission-line theory made the deeper significance apparent. A propagating mode itself possesses a characteristic impedance. When it encounters a load, reflection depends upon their relation:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}. \tag{3}$$

When

$$Z_L = Z_0, \tag{4}$$

the reflection vanishes.

This is the essential transition from *impedance* to *impedance matching*. The first can characterize an isolated system; the second exists only between interacting systems.

The principle is not fundamentally electrical. Mechanical impedance is

$$Z_m = \frac{F}{v}, \qquad [Z_m] = \mathrm{kg\,s^{-1}}. \tag{5}$$

Acoustics is one manifestation of mechanical impedance. The trumpet's exponential horn acts as an impedance transformer from pressure of the player's vibrating lips to the surrounding air.

Related matching principles govern electromagnetic propagation and optics. A freely propagating electromagnetic wave excites a characteristic ratio of electric to magnetic field; in vacuum,

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \simeq 377\ \Omega. \tag{6}$$

By the early twentieth century impedance had become much more than generalized electrical resistance. It characterized oscillatory systems and propagating modes. Matching governed reflection and transmission. Complex inductive and capacitive impedances governed amplitude and phase.

The timing is striking. Matter itself was about to become wave-like. De Broglie associated wavelength with massive particles, and Schrödinger constructed a wave mechanics in which reflection, transmission, interference, standing waves, and resonance became fundamental phenomena.

Classical physics already possessed a general relational principle for organizing precisely such behavior. Quantum mechanics reproduced it all. But it organized it differently.

3 Quantum Mechanics Takes Another Path

The problems that gave birth to quantum mechanics did not naturally ask for impedance. Planck confronted blackbody radiation; Einstein the photoelectric effect; Bohr atomic structure and spectra. Schrödinger asked for the equation governing the wavefunction and the boundary conditions selecting its solutions. Heisenberg emphasized observables and transitions. Born introduced probability amplitudes. Dirac and Jordan developed transformation theory. Later quantum field theory organized interactions in terms of propagators, vertices, amplitudes, and S-matrix elements.

This language succeeded spectacularly. There was little reason to reorganize the theory around an older classical concept. The classical question

How well are the interacting modes matched?

was distributed among several quantum questions:

What states are allowed?
What is the transition amplitude?
What fraction is reflected or transmitted?
When does resonance occur?
What is the scattering matrix?

Nothing was lost from the calculation. What disappeared was the unrecognized need for the organizing principle. This is one way a physical principle can become historically invisible without ever being disproved: another formalism calculates its consequences so successfully that the principle ceases to appear explicitly needed.

4 Bjorken and Feynman: Remarkable Near Misses

Impedance nevertheless repeatedly approached the center of quantum physics. A particularly revealing sequence occurred between 1959 and 1965, in works of both James Bjorken and Richard Feynman.

As outlined in his 1959 thesis[5], Bjorken discovered "...an analogy between Feynman diagrams and electrical circuits, with Feynman's regulators playing the role of resistance, external momenta as current sources, and coordinate differences as voltage drops. Some of that found its way into section 18.4 of..." the canonical text[6, 7]. As presented there, units of Feynman parameters are [sec/kg].

However, these are units not of resistance, but conductance. Units of mechanical resistance are [kg/s]. One would think more [kg/sec] means more mass flow. However, the reality is more [kg/sec] means more impedance, hence less flow. This topological inversion sits hidden in our systems of units[8]. While the network structure of quantum field interactions had become mathematically explicit, its intuitive advantage was lost with this unrecognized inversion.

Richard Feynman provides a remarkable thread through several of these encounters.

In 1959 Willard Wells completed a Caltech dissertation under Feynman's supervision on the reaction of a quantum-mechanical system upon a linear electromagnetic system[9]. Wells showed that the quantum system could be represented by an equivalent complex impedance together with an associated noise spectrum. Under population inversion its resistive component could become negative: the quantum system supplied energy to the electromagnetic network. A quantum system could therefore *present an impedance*.

Frank Vernon's work[10], subsequently developed with Feynman in the influence-functional formalism[11], approached the boundary from the opposite direction. A dissipative electromagnetic environment, characterized by response quantities including its impedance, acts upon a quantum system. The two directions were complementary:

$$\text{quantum system} \longrightarrow Z_{\text{eff}} \longrightarrow \text{electromagnetic system,} \tag{7}$$

and

$$\text{electromagnetic environment} \longrightarrow Z_{\text{env}} \longrightarrow \text{quantum system.} \tag{8}$$

Finally, in *Quantum Mechanics and Path Integrals*, Feynman and Hibbs discussed the boundary of a one-dimensional crystal[12]. A disturbance reaching the end of a finite chain reflects; continuing the chain appropriately eliminates the reflection. They described the boundary condition as analogous to terminating a transmission line in its characteristic impedance in order to avoid reflections. The principle itself had entered a quantum-mechanical problem. But it remained an analogy.

By the mid-1960s, therefore, several pieces lay remarkably close together. A quantum system could present an impedance. An electromagnetic impedance could act upon a quantum system. Feynman diagrams possessed an electrical-network representation. Impedance matching explicitly described reflectionless quantum propagation. None of this constituted a quantum impedance network. The question that remained unasked was:

What impedance does one quantum mode present to another?

5 Why Was the Connection Difficult to See?

No single historical cause explains why the pieces were not assembled.

One important circumstance was timing. The foundations of quantum mechanics and QED were already mature before von Klitzing's 1980 discovery of the integer quantum Hall effect[13] made **exact** impedance quantization spectacularly visible:

$$R_K = \frac{h}{e^2} \tag{9}$$

The characteristic resistance is fixed by fundamental constants. A macroscopic electrical measurement had become locked to an exactly quantized impedance.

A second issue was representation. Particle physics naturally adopted units in which

$$\hbar = c = 1. \tag{10}$$

Natural units greatly simplify quantum field theory, but they also remove dimensional signposts. In ordinary mechanical units,

$$[Z_m] = \text{kg/s} \tag{11}$$

announces mechanical impedance immediately. In natural units that clue disappears.

Bjorken's circuit analogy provides an especially intriguing example. The network was visible; the impedance was inverted. This parallels the history of the geometric wavefunction. A representation can preserve all the required physics while making a different physical organization difficult to see.

6 An Independent Route Back

The return to impedance came from an entirely different direction.

6.1 1975: Mach, a vibratory piledriver, and the two-body problem

The route that eventually led to quantum impedance networks began with Mach's principle and the mechanics of a vibratory piledriver. In such a machine, synchronous counter-rotating eccentrics add vertically and cancel horizontally, transforming 2D rotations to 1D translation, a Clifford product analog to Dirac electron and positron spinors counter-rotating in phase space.

The simplicity of this two-body mechanism provided an intuitive setting for thinking relationally about motion: rather than referring motion to an independently specified background, one asks what can be determined from the interaction of the bodies themselves.

Pursuing this question through Mach's principle led to a relational treatment of the two-body problem[14, 15, 16], beginning from

$$F = \frac{dp}{dt} = \frac{d(mv)}{dt} = m\frac{dv}{dt} + v\frac{dm}{dt}. \tag{12}$$

Rather than assuming constant mass and retaining only the first term, the two-body relational treatment excluded a background-dependent observer with respect to which orbital angular momentum could be defined. Attention was instead directed to

$$F = v\frac{dm}{dt}. \tag{13}$$

The resulting quantity had dimensions

$$\left[\frac{dm}{dt}\right] = \text{kg/s}. \tag{14}$$

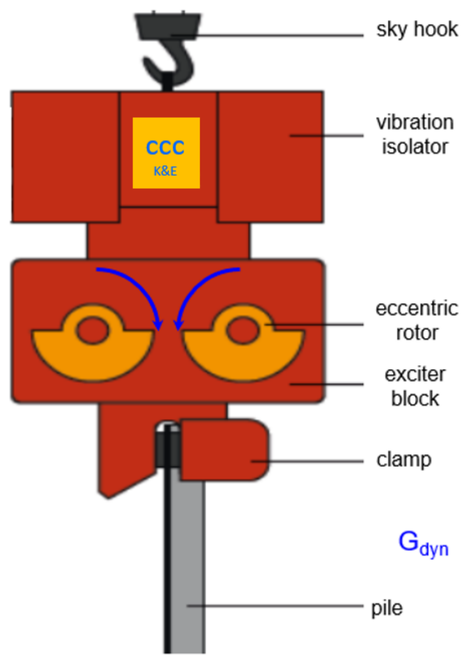

Figure 1: Vibratory Piledriver

Applied to the gravitational force of the Moon orbiting the Earth, the Coulomb force in the hydrogen atom, and gravitational escape velocity, the calculation reproduced the expected numerical relationships, but the physical meaning of the resulting quantity remained obscure. The 1975 treatment was submitted to the *American Journal of Physics* but not published. More importantly for the present history, the physical meaning of kg/s was not recognized.

For thirty-five years it remained an unusual dimensional result.

6.2 2010: A music studio and the missing recognition

The connection finally came from an unexpected source.

While building a home music studio with the author's musician son, the physics of musical instruments[17] led naturally to acoustics and acoustic impedance. Acoustic impedance is a form of mechanical impedance, and its dimensional structure made the old result suddenly recognizable:

$$\text{kg/s} = \text{mechanical impedance.} \tag{15}$$

The significance of the 1975 calculation had been hiding in its units.

The recognition was accidental, but what followed was not entirely so. During the intervening decades the author had worked as an instrumentation specialist at Brookhaven National Laboratory. Much of that work concerned amplitude and phase, phase-locked loops, coupled modes, transfer functions, feedback, and accelerator beam dynamics. Development of feedback systems for betatron tune, coupling, and chromaticity at RHIC, the Tevatron, and the LHC provided an especially direct education in the behavior and control of phase in coupled dynamical modes[18, 19].

Brookhaven did not supply the immediate recognition of kg/s. The music studio project did. But the instrumentation experience provided much of the conceptual conditioning through which the implications of that recognition could subsequently be pursued.

6.3 Quantized mechanical impedance

Once kg/s had been recognized, the next observation was elementary. All massive particles have mechanical impedance. Mass is quantized. Therefore massive quantum particles have quantized mechanical impedances. The question was no longer whether mechanical impedance existed in quantum systems, but what its allowed values were and how those impedances were related[15, 20, 21].

At this point the mature Impedance Model did not yet exist. Neither geometric algebra nor the electromagnetic coupling constant had been used as the starting point. Those connections came later.

7 A Synthesis Discovered Backward

What followed was a succession of unexpected recognitions.

7.1 MacGregor and α

In approximately 2011–2012, the node spacing of the calculated quantum impedance networks (QINs) was recognized as corresponding to powers of the fine-structure constant α. This was particularly striking because Malcolm H. MacGregor had independently spent decades investigating empirical α-spaced regularities in particle masses and lifetimes[22, 23, 24]. The two programs had arisen from different directions. MacGregor began with particle phenomenology. The QINs arose from impedance calculations. Their common α-spacing provided an unexpected connection between the developing impedance model and particle physics.

7.2 Matching to the Planck scale

In 2012–2013, extending the impedance network toward the Planck scale shifted attention from impedance values to impedance *mismatch*. The resulting relationships suggested an interpretation connecting the enormous relative weakness of gravitation with impedance mismatched electromagnetic interaction[25, 26]. Historically, this marked an important transition. Impedance was no longer merely a quantity associated with individual quantum modes of particle physics. The classical relational principle - matching between modes - was becoming central.

7.3 The gang of eight

A further serendipitous discovery came in 2015. The 2010 elementary calculations involving Coulomb, dipole, and scalar and vector Lorentz forces had generated eight structures, initially called the 'gang of eight'[15]. They had not been derived by starting from Clifford algebra. Only afterward was it recognized that they already possessed the (1,3,3,1) scalar, vector, bivector, and pseudoscalar organization of three-dimensional geometric algebra.

This was a major convergence with the first lost organizing principle considered in the companion essay[1]. The impedance calculations had independently arrived at a structure that was already written in the geometric language of the Pauli algebra vacuum wavefunction.

7.4 α moves to the beginning

One final retrospective recognition substantially simplified the model. The early field and impedance calculations had employed the fundamental constants e, ϵ_0, $\hbar$, and c, while α-spacing subsequently became conspicuous in the resulting QINs. Only later was the construction explicitly reorganized around the fact that these are precisely the constants defining

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}. \tag{16}$$

By 2019 this interpretation was explicit in work by Michaele Suisse and the present author[27]. Suisse, as first author, deserves particular credit for bringing the coupling constant to the beginning of the construction. This chronology matters because the mature formulation makes the model appear far more deductive than its history actually was. Today it can be written approximately as

$$\boxed{\text{geometry} \longrightarrow \alpha \longrightarrow \text{physical fields} \longrightarrow \text{quantized impedances} \longrightarrow \text{QINs} \longrightarrow \text{matching.}} \tag{17}$$

Seen retrospectively, this sequence of discoveries bears little resemblance to the path by which the mature model can now be constructed. Mechanical impedance, the α-spacing, Planck-scale matching, geometric algebra, and finally the foundational role of α were recognized successively, often only after the relevant structures had already appeared in the calculations. The mature synthesis was not the premise from which the model was constructed. It emerged from the convergence of initially independent observations.

There is another way to characterize this history. The mature construction became progressively more economical as independently discovered elements were recognized as consequences of a smaller set of inputs. This observation later motivated the consideration of the Impedance Model in terms of naturalness: whether a model beginning from minimally assumed geometric structure, a dimensionless coupling constant, and a single mass scale can generate rather than assume increasingly complex physical structure[31]. In this sense, the historical development described here exhibited an unusual direction of travel: increasing synthesis was accompanied by decreasing input.

The synthesis was discovered backward.

8 The Two Histories Converge

In the first history, the minimally complete Pauli algebra supplies the scalar, vector, bivector, and pseudoscalar components of the vacuum wavefunction. In the second, independently calculated Coulomb, dipole, and Lorentz interactions generated the same eight-component structure, now carrying quantized mechanical and electromagnetic impedances. What had begun as an engineering-style calculation of interactions was therefore found to inhabit the geometric representation of the quantum wavefunction.

The two questions are complementary:

$$\begin{aligned}&\text{Geometry: What modes does the wavefunction permit?}\\&\text{Impedance matching: How do those modes interact?}\end{aligned} \tag{18}$$

A later application provided a direct example of this relational picture. An attempt to calculate the neutrino PMNS mixing matrix began by representing the propagation modes by quantum impedances and seeking mixing amplitudes generated by the resulting network. Unexpectedly, amplitudes that emerged were recognized as those of the closely related quark CKM matrix, where all nine matrix elements could be reproduced to approximately one-percent accuracy using three topological impedances and the electromagnetic coupling constant α[28].

The corresponding neutrino problem remains more subtle. For the massive quarks the QED mass gap provides a natural phase reference, whereas in the massless-neutrino construction that gauge fixing is unavailable. Thus the unsuccessful attempt to calculate PMNS led serendipitously to the successful CKM calculation, while leaving the neutrino mixing matrix as an unresolved problem of phase and gauge fixing[29].

With the later recognition of the role of α, the mature construction can be expressed as

$$\boxed{\text{geometric wavefunction} \longrightarrow \alpha \longrightarrow \text{physical fields} \longrightarrow \text{QINs} \longrightarrow \text{amplitude and phase.}} \tag{19}$$

This convergence is the central historical result. Neither geometric algebra nor impedance matching was introduced at the outset to produce the other. They entered the developing model by independent routes and were recognized only later as complementary descriptions of the same network of wavefunction interactions[30].

9 Conclusion

Impedance matching was not absent from quantum physics. Its consequences remained everywhere, and impedance itself repeatedly appeared at the boundary between quantum systems and classical networks. What failed to emerge was impedance matching as a general organizing principle for interactions among quantum modes.

The independent history traced here approached the problem from the opposite direction. A mechanical quantity obtained in 1975 but left physically unidentified was recognized thirty-five years later as impedance. The resulting quantum impedance calculations subsequently encountered, rather than assumed, the α-spacing of particle phenomenology, Planck-scale matching, and the geometric structure of the Pauli algebra. Only later was α itself moved to the beginning of the construction. Seen retrospectively, this progression toward fewer assumptions and greater emergent structure also raises the question of naturalness[31].

The two histories considered in this and the companion essay therefore meet at an unexpected point. Geometry identifies the possible modes of the wavefunction; impedance matching provides a relational description of their interaction. Both structures were present in twentieth-century physics. What was lost was their visibility as organizing principles.

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