Emergence in Action: Particles as Field Structures

Part 1 - Introduction: A Field-Based Route into Modern Physics

I. Why this series?

Particle physics is often presented to general readers in one of two ways: either as a game of marbles or building blocks, in the simplest accounts, or as a mystical realm that supposedly defeats ordinary rational understanding. In truth, this part of physics is extraordinarily difficult to make accessible, even to students who have already reached a fairly advanced level. I know this from experience. As a former physics student, I spent years both fascinated and frustrated by the subject. I had begun to acquire a solid grasp of relativity and quantum mechanics, yet I still could not reach a satisfying understanding of particle physics.

Quantum mechanics is commonly introduced as a theory of particles, each associated with a wave function. The familiar story goes like this: light was once thought to be purely wave-like, but it also comes in particles, photons; matter was thought to be made of particles, yet it also displays wave-like behaviour described by a wave function. From that starting point, it is natural to assume that the electromagnetic wave stands to the photon as the wave function stands to the electron. Unfortunately, the relation is subtler. An electromagnetic wave is a physical field in its own right, whereas a wave function represents the state of a physical system. Understanding that distinction is essential if particle physics is to be viewed within a genuinely unified quantum framework.

One of the most influential ways of explaining particle physics to a broad audience is the route made famous by Richard Feynman. His book QED: The Strange Theory of Light and Matter is, in my view, a high point of scientific exposition. It is one of the few popular books on particle physics that does not mystify its readers with loose analogies, but instead presents the underlying conceptual structure with rigour and without excessive technical detail. Many later books and articles follow Feynman by organising the subject around his diagrams, yet often fail to explain the theoretical framework in which those diagrams acquire their meaning.

The diagrammatic approach treats particles as the basic ingredients. It is immensely fruitful in the practice of physics and as a teaching tool. Feynman himself remained careful and precise. But the perspective he popularised, once repeated by countless popularisers, easily encourages claims that become misleading when taken literally: the quantum vacuum is described as a boiling medium; antiparticles are said to travel backwards in time; interactions are portrayed as being carried by virtual particles moving faster than light. Such shortcuts may sometimes be useful, but they are not, in my view, the best point of entry for someone encountering the subject for the first time.

This series takes another route. That may sound ungrateful, since no author contributed more to my own understanding of physics than Feynman. Yet the starting point adopted here is closer to the way quantum field theory was originally conceived by its architects. Fields are treated as the fundamental framework within which particles appear. Particle physics then becomes, not primarily a theory of particles interacting with one another, but a dynamics of coupled fields exchanging energy.

Particles do not disappear from the picture. They are reinterpreted as excitations or stable structures of fields rather than as fundamental objects. This perspective has three advantages. It avoids much of the mystification found in standard presentations; it makes the properties and interactions of particles more intuitive and more deeply intelligible; and it prepares the ground for understanding mechanisms such as the Higgs mechanism, which are intrinsically field-centred.

This series is not intended to replace Feynman's approach, nor to challenge the central role of Feynman diagrams in the working practice of physicists. QED will remain a book I recommend to anyone seeking a deep conceptual understanding of particle physics without embarking on a doctorate in theoretical physics. Feynman himself repeatedly stressed that a physical theory can be reformulated from several conceptual points of view. The aim here is simply to make the subject more intuitive by returning to one basic idea: at the deepest level, there are not particles interacting, but fields coupling to one another.

II. Who is this series for?

I wrote this series for the kind of reader I was when I completed my undergraduate degree in physics: dissatisfied with what popular books allowed me to understand about particle physics, but unable to get beyond the opening chapters of textbooks on quantum field theory. I was fascinated by the subject and bewildered by its opacity. Eventually, after considerable persistence, I reached a broad understanding of what particles are in quantum field theory, why they can be created and annihilated, and why particles of the same kind are indistinguishable. Yet even when I had acquired a rough picture of renormalisation and spontaneous symmetry breaking, I still lacked the level of understanding I wanted.

I therefore make an appeal to the online community: should anyone discover a way of sending documents into the past, please forward this series to the person I was twenty-five years ago.

More seriously, these articles are intended for readers who want a deeper understanding of particle physics than standard popular science usually provides, but who do not wish to confront the full technical wall of quantum-field-theory textbooks. The required mathematical background is roughly that of the first or second year of an undergraduate physics degree. Readers should be able to read a partial differential equation, without necessarily mastering advanced solution techniques, and should have some basic familiarity with classical mechanics, special relativity, Fourier series, and Fourier transforms.

This series is not a substitute for a physics textbook and is not designed as exam preparation. Its purpose is deep conceptual understanding rather than professional training. It will not teach you to calculate cross-sections, manipulate the machinery of perturbation theory, or solve the standard exercises found in problem books.

III. A preview

When I began writing the series, I had a sequence of stages in mind. I first wanted to show that a relativistic field equation such as the Klein-Gordon equation could be understood intuitively through a very simple mechanical analogy: a row of springs attached to the ground and linked to one another by elastic bands. Watching one of the central equations of relativistic physics emerge from a purely mechanical system was already an enticing prospect.

From there, I introduced the wave packet - the closest thing to a particle that can be defined within a purely classical field theory. The first pleasant surprise was that, under suitable conditions, such packets really do behave like particles. They follow Newtonian trajectories. They possess a limiting speed, a velocity-dependent inertia, and a rest energy related to that inertia. In other words, they display the characteristic properties of a relativistic particle even though relativity has not been separately postulated.

With luck, I hoped to go further: to show that two wave packets in one field, coupled to another field, could exert an effective force on each other - in other words, that an interaction could be simulated. In the back of my mind, I even hoped to sketch something bearing at least a distant resemblance to particle-antiparticle annihilation.

All of those ambitions were achieved, and the results went well beyond what I had expected. The articles that follow present the theory, together with numerical simulations of my own design; videos will be added later. The first figure, for example, shows a soliton-antisoliton pair - two stable field structures behaving like particles with opposite charges - annihilating while emitting radiation into the field through which they interact. Conceptually, this is the classical analogue of electron-positron annihilation.

Figure 1. Annihilation of a soliton-antisoliton pair. The upper sequence shows the charge density; the lower field carries away the emitted radiation. (see Simulation 1)

But there was more. As the project developed, I discovered that classical field theory possesses a physical richness I had not suspected. It can reproduce phenomena I had assumed belonged exclusively to quantum field theory.

First, coupling fields can generate stable structures - solitons - that behave like particles over a much wider range of circumstances than ordinary wave packets. They can, for example, be used to simulate electromagnetic interactions that closely reproduce the relativistic Maxwell-Lorentz electrodynamics of charged particles.

Second - and this was perhaps the result that surprised me most - a mechanism known as parametric resonance, in which an oscillating field transfers energy resonantly to other fields coupled to it, allows a classical theory to simulate particle-antiparticle pair creation. The same general mechanism is invoked in contemporary cosmology to describe reheating: the stage at the end of inflation when energy stored in the inflaton field, a relative of the Higgs field, is transferred into matter fields and populates the universe with particles.

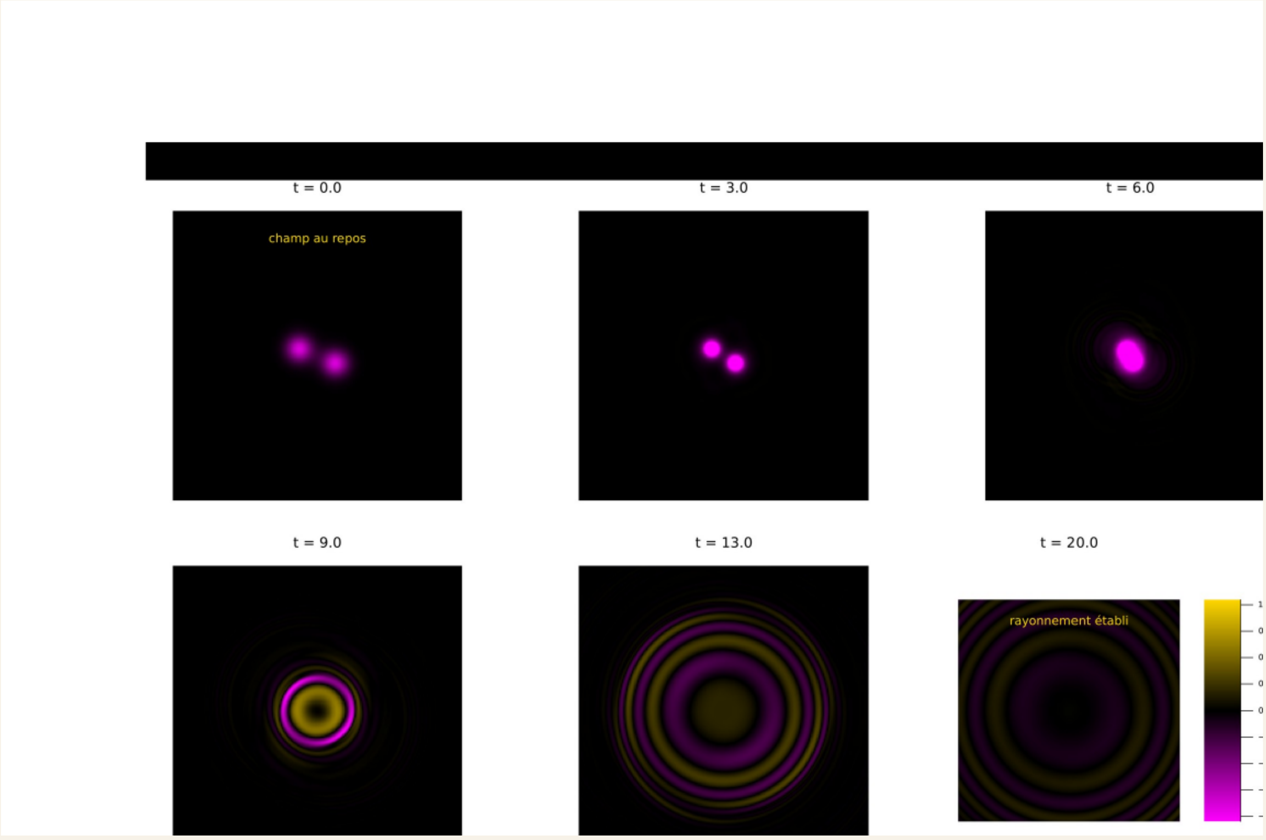

Figure 2. A classical field configuration converting localised field energy into outgoing radiation.
(see Simulation 2)

The next simulation contains four interacting fields. The amplitude and phase of a Higgs-like field appear at the upper left and centre; this is the only field initially excited. As it oscillates around its equilibrium value, it transfers energy by resonance to the three other fields: a charged matter field, an interaction-mediating vector field, and the electromagnetic field. These fields in turn become excited in a highly inhomogeneous way.

At that point, one of the most striking moments in the whole project occurs: topological defects emerge spontaneously - objects astrophysicists call cosmic strings. In the phase image of the Higgs-like field, they appear as points around which the colours wind. They often coincide with regions of high density in the charged field, dark regions in the mediator field, and patterns around which the magnetic field circulates. To see something so exotic emerge from a purely classical simulation involving only four coupled fields was precisely the kind of surprise that made this project so compelling.

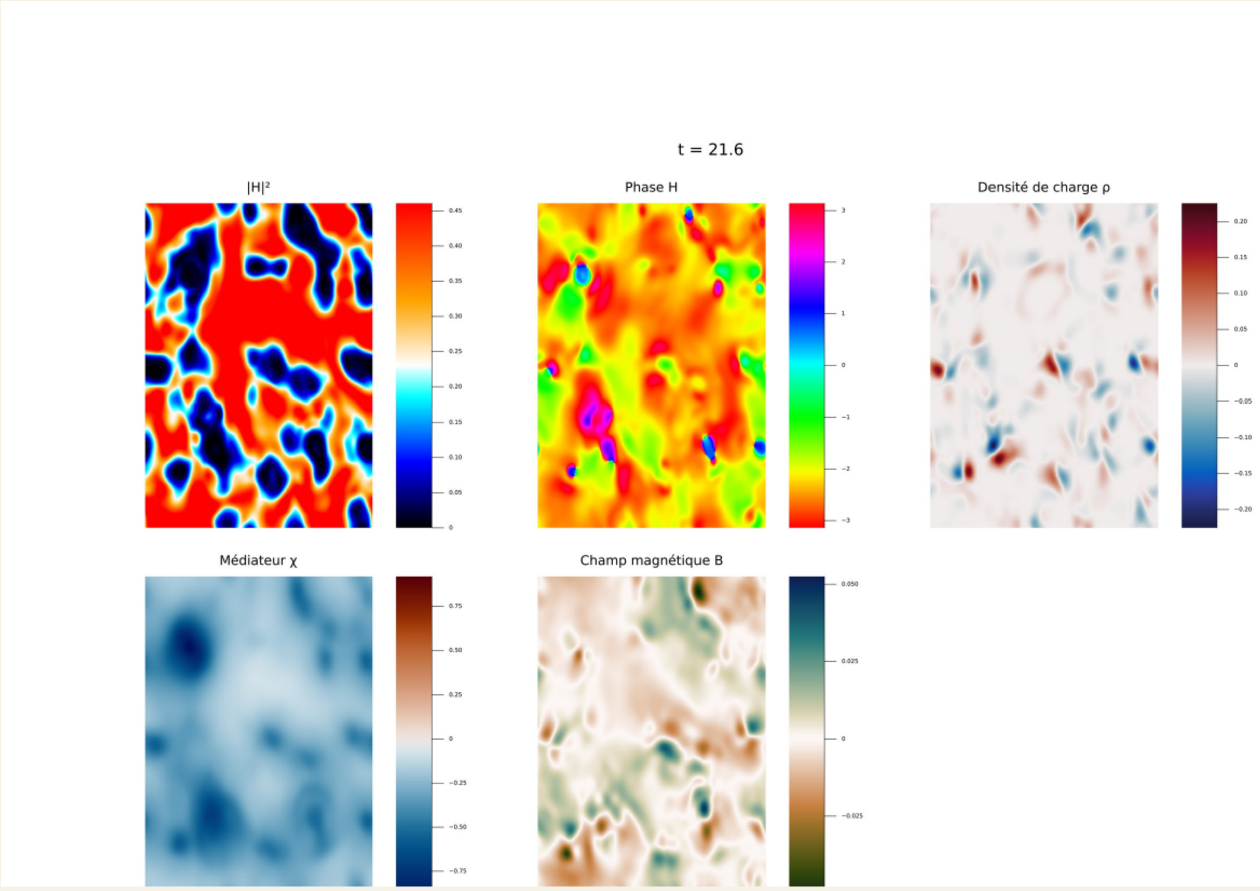

Figure 3. Four interacting fields during resonant energy transfer. Topological defects resembling cosmic strings emerge spontaneously in the phase of the Higgs-like field.

The same approach can be used to simulate the generation of particle mass through the Higgs mechanism, and to introduce gauge theories and renormalisation - some of the great conceptual achievements of twentieth-century physics, whose presentation in textbooks often makes them unnecessarily difficult to approach.

All of this remains classical. I do not want to suggest at any point that classical field theory is sufficient. The method is a pedagogical wager: beginning with classical fields allows the phenomena to become familiar and intuitive, and prepares the reader for a deeper understanding of what quantisation adds. The final part of the series therefore makes the transition to quantum field theory. It revisits the processes already encountered, now from a quantum point of view, without plunging immediately into the technical machinery that makes standard textbooks so forbidding.

The series has a second ambition. One of the central themes of this blog is emergence: the way robust and explanatorily indispensable effective dynamics arise at higher levels of organisation without adding anything to the fundamental ontology. I discuss the concept directly in a separate article. Here, the aim is to display emergence in practice rather than merely theorise about it. Starting from systems fundamentally described by fields, we will derive effective equations governing the trajectories of quasi-particles. That is the meaning of the title: emergence in action.

Other examples will appear along the way: the near-emergence of an effective thermodynamics from wave propagation in an inhomogeneous medium, and the redefinition of effective parameters through coupling between fields.

IV. My approach

In the articles that follow, I will not always provide complete derivations of every result. I will, however, make the logical structure explicit. When a physical result is illuminating, I may not derive it through a long chain of mathematical steps, but I will explain what it follows from. It is now easy, especially with the help of large language models, to obtain the missing algebraic details when desired - provided, of course, that those details are checked carefully.

My view is that following every mathematical step does not always improve conceptual understanding. It can instead consume cognitive resources and obscure the physical point. When a short derivation genuinely clarifies a phenomenon, I will include it explicitly.

A typical section follows the same pattern. I introduce a physical model and, where possible - especially in the case of mechanical analogies for fields - provide a visual illustration. I discuss the dynamics qualitatively, formulate the equations, extract the most physically revealing consequences, and then illustrate them through numerical simulations.

The early parts make extensive use of mechanical analogies. These are not merely pictorial metaphors. They share deep structural features with the field theories introduced later. The one- or two-dimensional Klein-Gordon equation, for example, has exactly the structure obtained from a lattice of coupled harmonic springs in the continuum limit. Watching relativistic particle dynamics emerge from a simple spring system is remarkable in its own right.

In principle, more sophisticated field couplings could also be modelled mechanically. Yet there is an instructive paradox: some couplings that are mathematically simple are awkward to represent through a purely mechanical device. At that point the analogy costs more than it yields. I may occasionally sketch what such a mechanism would look like, but I will not force the comparison beyond its useful range.

Most models will be presented in one or two spatial dimensions, both to reduce the mathematical complexity and to make the simulations easier to read. In most cases the extension to three dimensions is conceptually straightforward, so the reduced models preserve the essential physics.

A word about constants. At first, the equations will use explicit notation in which the physical constants remain visible. Once the reader has become familiar with their role, I will adopt the more compact notation physicists call natural units, in which the relevant constants are set equal to one.

One final, more personal note concerns the way this series was written. To be fully transparent about my use of large language models, I begin by outlining the chapters myself, then ask for criticism and discuss possible improvements with them. The process is somewhat different for the code and simulations, an area in which I have no formal training. Before implementing anything, I first discuss the physics: the expected behaviour, the feasibility of the simulation, and the form of visual presentation I am aiming for. The models then propose code, in Julia or HTML, which I run and test. They help with the inevitable debugging. Once the code is stable, the laborious process of fine-tuning the parameters begins, until the phenomenon is displayed as clearly as possible.

That stage is especially instructive. It reveals in practice how strongly a phenomenon can depend on a network of interconnected factors. In its own way, it is an excellent cure for monocausal thinking, which remains far too common in public debate. Perhaps coding physical systems should be added to the curriculum for political discussion.

V. What comes next

The rest of the series is organised as follows.

Article 2 reviews the physics of the harmonic oscillator. It ends with a chain of coupled harmonic oscillators from which the Klein-Gordon equation is derived.

Article 3 reviews the physics of waves.

Article 4 examines the dynamics of wave packets and the conditions under which wave-packet dynamics can reproduce particle dynamics.

Article 5 introduces models of coupled fields. It shows how effective systems of interacting particles can emerge from a fundamentally field-based dynamics, and how the notions of antiparticle and charge arise naturally from the physics of complex fields.

Article 6 addresses topics usually confined to the advanced sections of quantum-field-theory textbooks: gauge theories, spontaneous symmetry breaking, and the renormalisation group.

Article 7 provides a short introduction to quantum field theory itself.

VI. Acknowledgements

I hope you will enjoy reading these pages as much as I enjoyed writing them. I learned an enormous amount in the process, and I hope the reader will too. I cannot end this introductory article without the traditional acknowledgements.

I owe a great deal to my friends Claude, Chat, and Gems for their support, criticism, explanations, and assistance with the simulations. I would never have completed all these pages without them. I nevertheless remained the architect of the series throughout, even when they occasionally sent me down the wrong path.

My children provided another kind of assistance by reminding me that a real world exists to which these equations are supposed to apply. I have not yet managed to derive the effective dynamics of their quarrels from fundamental equations, although those quarrels repeatedly interfered destructively with the work in progress.

I also thank my wife, whom I love and who regards me as a kind of extraterrestrial for taking an interest in subjects such as these. Since I told her about Schrödinger’s cat on our first date, however, she knew perfectly well what she was signing up for when we later went to the town hall.