String theory deconstructed

Dedicated to the memory of Klaus Pohlmeyer

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Abstract

This essay presents a critical evaluation of the concepts of string theory and its impact on particle physics. The point of departure is a historical review of four decades of string theory within the broader context of six decades of failed attempts at an autonomous S-matrix approach to particle theory.

The central message, contained in sections 5 and 6, is that string theory is not what its name suggests, namely a theory of objects in spacetime whose localization is string-like instead of point-like. The result is corroborated by the failure of the conformal embedding interpretation. Whereas the "target space" of the chiral theory (higher dimensional vector or spinor indices of currents) defined by the inner symmetry indices of an abelian current is redefined as the spacetime of string theory, the one-dimensional chiral conformal "source" theory is not embedded as a string in target space but rather the oscillators of the would-be string go into an infinite dimensional inner Hilbert space pictured as an inner space over a localization point in target space. Hence string theory solves a problem which enjoyed some popularity in the 60s namely the construction of dynamical infinite component fields. This means in particular that there are no word-sheets which can be subjected to interactions in form of ruled for tubes in analogy to Feynman graphical rules.

The present work also subjects ideas to a critical test which arose in the wake of string theory, as dimensional curling up, the quantum theoretical aspects of branes and the Maldacena conjecture.

The essay is dedicated to the memory of Klaus Pohlmeyer since he studied the intrinsic physical content of the Nambu-Goto Lagrangian as an autonomous quantum system according to Faddeev's ideas concerning integrable systems. This leads to a system which, as QFT, exists in every spacetime dimension and is inequivalent to the above infinite component field of string theory.
1 Preface

Tracing ideas, which have been dominating for decades large parts of particle theory, back to their historical origin is usually considered interesting worthwhile only in case there is a happy end, which in particle theory means a theory whose success is universally recognized. This is certainly the case with renormalized quantum field theory (QFT) and in particular quantum electrodynamics (QED) which gloriously confirmed the ideas about quantization of relativistic matter waves at the cradle of quantum field theory. This essay presents a critical look at a less successful but already almost 5 decades lasting project which, since the 80s, became popular under the name of string theory.

Particle theory, being an extremely speculative science at its frontiers, comes with a large list of failed projects which is much longer than that of successful ones. Most have been left on the wayside of the great particle physics caravan, in fortunate cases after having received critical attention and an appropriate closure. Who still remembers the frenzy about combining inner symmetries with the relativistic spin under the name "SU(6)", the "peratization" of quantum field theory (the precursor of "effective QFT"), or the Lee-Wick model (complex poles finally shown to lead to acausal precursors)?

Failed projects which managed to hang on for a decade, as the S-matrix bootstrap in its role of a unique theory of strong interactions, are more rare and hence they stay longer in our memory, especially if some of their content is reprocessed and together with other ingredients used as raw material of a new theory, as it was the case with string theory.

In this area of tension between successful and failed ideas, string theory plays a special role. The opinion on this issue is still split and if issues in particle physics could be decided by a democratic vote, string theory would most probably continue in a limbo. But, as the history of particle physics amply demonstrates, popularity is not always coupled to the scientific solidity of a theory; the vernacular "so many people cannot err" is in fact turned on its head in particle theory by the observation that the larger the community around a fashionable failed topic, the lesser the possibility of an internal critical view and the more fades the chance to overcome the derailment. This point is especially relevant since the old "Streitkultur" which in the 50s and 60s provided a critical counterbalance to speculative new ideas discontinued in the 80s and many those who in earlier times were, as the result of their scientific status, the natural pundits for analyzing new ideas, are now their fiercest defenders, if not to say their salesmen.

It is impossible to criticise string theory in a profound scientific manner by only looking at the present situation, and a reconstruction of the sudden changes in the 5 decades old history and its Zeitgeist is not really achievable without having lived through at least part of that time and in this way having acquired a first hand knowledge. After all the conceptual errors have been committed at the beginning (in the transition from the S-matrix bootstrap to the dual model) and then propagated into the present problems. These problems will be in the focus of this essay.
2 How it all began, a historical sketch of the path from QFT to S-matrix theories and back

Nowadays there is agreement that the history of QFT started with Pascual Jordan, one of Max Born’s young collaborators. But simply stating this does not explain Jordan’s radical viewpoint about field quantization which certainly was not shared by his friendly adversary Paul Adrien Maurice Dirac, at least not up to 1950 when Dirac came around to embrace field quantization as a general principle. At the time when Jordan pleaded to apply the quantization formalism also to matter (de Broglie) waves, Dirac limited field quantization to light, whereas (massive) matter was subject to the Born-Heisenberg rules of quantum mechanics [2].

The radicality of Jordan’s view has its explanation in an episode 1925 when Einstein roughened Jordan’s feathers about some points in his 1924 thesis “Zur Theorie der Quantenstrahlung”. Shortly afterwards Einstein wrote a counter-article against Jordan’s claim that in getting thermal equilibrium between electromagnetic radiation and material oscillators one does not have to make Einstein’s ”Nadelstrahlung” (needle radiation, his way of getting corpuscular photons into the picture) assumption of a radiation recoil $\hbar c$; an assumption which naturally fitted into his 1905 idea of what received later the name photons.

Einstein showed that Jordan’s claim, although mathematically correct, came into a contradiction with physical facts because such a theory could not explain the absorption coefficient. The impact on the young Jordan was profound, he not only convinced himself that the quantization of electromagnetic radiation led to Einstein’s corpuscular view of light, but he also took this as a starting point to elevate wave quantization of matter to a general principle; such giving de Broglie’s ideas the missing conceptual-mathematical underpinning.

Dirac on the other hand defended his view that, although classical waves as electromagnetic radiation must be quantized, the classical-quantum parallelism called appropriately ”quantization” is best served by using quantum mechanics for the description of massive quantum matter and reserve field quantization to electromagnetism. Many successful ideas appeared to support his viewpoint; in particular because it led Dirac to his seminal relativistic equation, which in turn opened the path to a deep understanding of the relativistic spin equation and the hole theory of the electron/positron system. The first textbooks on relativistic particle theory by Heitler and Wenzel were based on the Dirac’s hole theory of particles; and as long as the perturbative order was low enough in order to avoid vacuum polarization contributions (as in those books), hole theory led to consistent and observationally verified results.

But hole theory becomes inconsistent in the presence of vacuum polarization; renormalized QED cannot be formulated and performed in Dirac’s hole theory setting. Dirac’s long lasting detour to QFT was probably the conceptually richest odyssey in particle theory. The conceptual and physical differences between QM and QFT (historically represented by Dirac and Jordan) are most pronounced in the ubiquitous presence of vacuum polarization in all processes.
which deal with localized objects (as distinct from global quantities as the scattering matrix). To be more precise, the only local objects which are free of vacuum polarization are free fields themselves. But as Heisenberg had shown, sharply localized (Wick-ordered) functions of free fields (composite fields), in particular the quadratic function representing a partial charge,

\[
Q_{R,\Delta R} = \int_{|x| < R + \Delta R} \frac{d^3x}{|x|} j_0(x) f_{R,\Delta R}(x), \quad f_{R,\Delta R}(x) = \begin{cases} 
1, & |x| < R \\
0, & |x| > R + \Delta R 
\end{cases}
\]

where the quotation mark is an alert that the current-charge connection in QFT requires the definition of the current as a "normal product" (Wick product in the free field case) and a definition of the integral (in view of the fact that the integrand is an operator valued distribution). The test function \(f_{R,\Delta R}\) localizes spatially in a smooth way. In case one is interested in the global charge limit \(R \to \infty\), the specification in what sense of operator convergence the integral converges (weakly, strongly).

Heisenberg showed that if one integrates the charge density over a sphere of radius \(R\), which corresponds to the limit \(\Delta R \to 0\) and fixed \(R\), the integral diverges as a result of vacuum polarization caused by the current density acting on the vacuum. The discovery of vacuum polarization in composites of free field operators and the subsequent observation by Oppenheimer and Furry that the presence of interactions leads to infinite vacuum polarization clouds (finite in every finite perturbative order, increasing with order), are in a retrospective evaluation the conceptually most important contributions to the early phase of QFT.

For the first time it delineated QFT clearly from any form of relativistic QM. In principle a profound understanding for the ubiquitous presence of vacuum polarization as a consequence of causal localization could have saved QFT from its first big crisis, the ultraviolet divergence crisis, which however, different from the later crisis which will be the subject of this essay, did receive a proper closure.

Part of this crisis was overcome by mathematics, namely the recognition that, very different from classical theories and also different from quantum mechanics, quantum fields are singular by their very nature and manipulations with them go astray if one does not keep the Laurent Schwartz distribution theory at least in the back of one’s head in dealing with quantum fields. This lead to a flurry of articles around the beginning of the 50s in which the new message was that quantum fields are really operator-valued distributions. These mathematical structures, which made QFT so different from QM, had their origin in the phenomenon of vacuum polarization (and different concept of localization from the Born localization of Schroedinger wave functions) which renders quantum fields as objects with a short distance behavior which was never seen in QM.

In the case of the above partial charge this connection can be nicely exemplified. A sharp localization of e.g. the charge density within a radius \(R\) causes infinite vacuum polarization clouds which manifest themselves in the contributions of infinitely many intermediate vacuum polarization formfactors

\[
\langle p_1, \ldots, p_n | j_0 | 0 \rangle
\]
which enter the calculation of the $\Delta R \to 0$ singular behavior of the norm of the partial charge applied to the vacuum which for dimensional reasons is (modulo logarithmic corrections) proportional to $(R/\Delta R)^2$ since the region of the vacuum polarization grows with the area of the shell around the sphere of radius $R$ and $R$ and $\Delta R$ are the only dimensionful quantities\[1\]. This dependence on the "thickness" of the vacuum polarization cloud hold also for other dimensionless quantities which diverge if one compresses the fuzzy localization of the vacuum polarization cloud in the attenuation shell by sending the attenuation collar $\Delta R \to 0$.

One such quantity which has been the object of recent studies is the "localization entropy" \cite{80} which, like the charge, is also dimensionless and diverges in the same way. In the limit $R \to \infty$ the vacuum fluctuations disappear and the value of the charge or the entropy in the global vacuum vanish. The partial charge on the vacuum and the localization entropy, being both dimensionless, do not only have the same short distance behavior, but they also converge both to zero in the global limit $R \to \infty$.

The distribution-theoretical cure together with the principles of QFT allows to separate problems with genuine infinities, as for the partial charge or the localization entropy, from those which are "man-made" i.e. have been caused by using inappropriate physical concepts of QFT during perturbative calculations. All divergence problems at the time of the ultraviolet crisis in the decade before renormalization were of this kind. Even renormalization was often understood as the consistent removal of cutoffs or regulators; this is perfectly reasonable as long as one does not attribute any physical significance to such computational tricks. This way of looking at dynamical formulations of QFT in the old says came from QM, where the main dynamical problem was to convert formally defined operators into mathematically well defined selfadjoint or unitary operators and to compute their spectrum and eigenstates. The most important operator of this setting is the Hamiltonian.

The conceptual setting of QFT is radically different. Here the main tool for the classification and construction of models is the *realization of the locality principle*. This is particularly evident in the formulation of Epstein and Glaser. One starts with an invariant interaction polynomial formed from covariant free fields which in turn are obtained from the covariantization of the Wigner representation. There are many free fields for a given $(m, s)$, whether they are of the Euler-Lagrange kind or not is irrelevant at this point\[2\] since strictly speaking this is not a Lagrangian approach. The Epstein-Glaser iteration step consists in showing that the n-fold time ordered operator products in the next perturbative order are determined from the previous order, apart from the spacetime diagonal. These freedom to add "counterterms" on the total diagonal is restricted by a scaling requirement: do not add counterterms with higher scaling degree than that before the addition of counterterms.

\[1\]Although this argument is only valid in conformal models, it is believed that the value of the mass does not enter the leading behavior.

\[2\]What is relevant for passing the renormalizability test is that the fields have their smallest possible short distance dimension which is 1 for Bosons and 3/2 for Fermions.
Models are called (perturbatively) renormalizable if the scaling degree subjected to those rules does not increase with perturbative order. In $d=1+3$ the number of renormalizable models turns out to be finite, only free fields with scaling degree one whose interaction polynomial has a scaling degree which stays within the power counting limit of 4 lead to renormalizable models. The latter form finite parametric islands among all couplings and all fields (the universal Bogoliubov generating $S$ operator) which are stable under application of the renormalization group and with only coupling pointlike fields, their number is finite.

From the vacuum expectation values of these time ordered operators one obtains via the so-called KMS construction a Hilbert space representation which contains all operators which are useful for the model, in particular the Hamiltonian. Cutoffs and regulators maybe convenient computational tricks in certain situations, but there is no conceptual necessity to work with them.

The described renormalization setting contains strictly speaking only $s = 0, \frac{1}{2}$ fields; $s = 1$ fields remain outside since the scaling dimension for the lowest dimensional pointlike field of spin $s$ is $d_{sc} = s + 1$ and $d_{sc} = 2$ is too high for the power counting limit; the prerequisite for renormalizability is $d_{sc} = 1$ which is the lowest value permitted by positivity (unitarity) in 4 spacetime dimensions. The saving grace came from an analogy with classical gauge theory where the vectorpotential is an important calculational tool. The prize for using such a vectorpotential in QFT is however quite high: in order to save its pointlike field formalism one has to overcome a clash between quantum localization and the fundamental Hilbert space setting of quantum theory, a clash which has no analog in the classical setting.

The way to do this is well-known: quantum gauge theory, formulated either in the older (and more limited) Gupta Bleuler setting or by using the more general and meanwhile better known BRST formalism. The indefinite metric lowers the short distance scale dimension down to the power counting range and at the end of the day, after all calculations had been done in the unphysical metric, the BRST "symmetry" allowed the return to QFT in form of finding a subalgebra pointwise symmetric under BRST transformation. In this way one can enlarge the range of renormalization theory to $s = 1$.

We owe all our insights into the standard model (the culmination of gauge theory which started with renormalized QED) to the formalism of gauge theory. But does this mean that gauge theory is the closure of an development which started with QED? Certainly not, the clash between pointlike localization of vectorpotentials (and more generally $(m = 0, s \geq 1)$ tensor-potentials) and the positivity principles of QT should not be solved by a technical trick but rather at its conceptual roots.

Even staying with $s = 1$ There are eminent practical reasons why one should not view the present gauge formulation to be the last word. Gauge theory only covers the very small subalgebra of local observables; all operators in QED which

\[3\] The improved short distance behavior from negative probabilities was used in innumerous forgotten short distance improving calculations.
carry electric charge remain outside its formalism; their presence is only symbolically indicated in the form of Dirac-Jordan-Mandelstam exponential semiinfinite line integrals whose perturbative definition and construction is not part of the QED perturbative renormalization formalism [5]. The Dirac spinors in the field equation or in the interaction Lagrangian have no direct physical significance, in fact it is known that there can be no nontrivial electric charge in an indefinite metric space [6]. The situation worsens for Yang Mills theories and QCD; in that case all spacetime dependent correlations have apparently incorrigible infrared divergencies and those few spacetime independent quantities which one can compute, as the beta-function, remain without those physical objects whose short distance behavior they are supposed to describe.

The way out consists of two steps [5]. The first step is a return to the Wigner representation theory in order to resolve the clash between localization and positivity right there. For the electromagnetic fields \((m = 0, s = 1)\) this is quite easy: although there is no pointlike covariant vectorpotential in the Wigner representation space, by relaxing the localization requirement one easily obtains a semiinfinite stringlike localized vectorpotential \(A_\mu(x,e)\) which is causally localized on the line \(x + \mathbb{R}+e\). This construction can immediately be generalized to \(s > 1\). The use of such string-localized potentials avoids fallacies of the indefinite metric pointlike vectorpotential e.g. the conclusion that the application of the Stokes theorem to the magnetic flux leads to a an object which is really localized on the boundary [7][5].

The second step consists in the use of the stringlike physical vectorpotentials in interactions. The power counting hurdle is easily passed since one can always construct string-localized potentials whose scale dimension is one, even for \(s > 1\). In fact these potentials were not totally unknown in the gauge setting, they are apart from important differences in interpretation identical to the axial gauge potentials and it was also known that they live in a Hilbert space. What was however overlooked was their stringlike localization. To be more precise, the main consequence of this localization, namely the incorrigible infrared divergencies (even in the QED correlations for charged fields) were noticed and led finally to the dismissal of this gauge.

But reinterpretting the alleged gauge parameter as a spacelike localization direction of a string \(e\) (a point in a lower dimensional de Sitter space) the fluctuations in \(e\) and the resulting distributional character are is hard to be overlooked. This mathematical situation asks for a smearing in the \(e's\) and a calculation of coincidence limits pretty much as one goes about composite fields in \(x\). There is also the problem of how to formulate the iterative Epstein-Glaser renormalization for strings [5]. The lower short distance dimension of string-localized potentials also carries over to the massive case which is of great relevance to the improved understanding of the Schwinger-Higgs screening mechanism. Needless to add that strings in QFT, gauge theory and the standard model have in content nothing to do with string theory; it is however one of our conclusions in this essay that the long period of stagnation in those areas is connected to the ascend of popularity of theories of everything (TOE) and string theory in particular.
The perturbative approach based on the local coupling of free fields is not a good starting point for mathematically rigorous model constructions, because even under optimal circumstances the renormalized perturbative series is known to diverge. In that case there exists a different strategy which is based on the philosophy that algebras with larger localization regions admit generators which have a lesser complicated vacuum polarization structure. For a certain family of two-dimensional models it was possible to find generators for wedge-localized algebras which are rather simple. The compactly localized double cone algebras can then be shown to exist in a nontrivial way, which secures the nontrivial existence of the theory with a clear path for the construction of pointlike generating fields.

Quantum field theorists and mathematical physicists in the old days also discovered a relation of a certain type of QFT (including those polynomial field couplings investigated at that time) with Euclidean QFT and Statistical Mechanics. In fact the contributions of E. Nelson, K. Symanzik, F. Guerra, K. Osterwalder, R. Schrader, J Glimm and A. Jaffe did not only form the focus of mathematical particle physics of the 60s, but they were also indispensable for the linkage with statistical mechanics and the formulation of Wilson’s renormalization group project.

The connecting link of the particle theory based on QFT and string theory, which will be in focus of our critical analysis in the present essay, is S-matrix theory. By this we do not mean Dyson’s presentation for the perturbative scattering matrix which presented the crowning finish of the first attempt at renormalized perturbation theory in the 50s, but rather the partially misled attempts to escape the perceived ultraviolet catastrophe in pre-renormalization times by exclusively dealing with operators which are free of vacuum polarization clouds.

These attempts led around 1942/43 to Heisenberg’s proposal to study autonomous theories of S-matrices i.e. models which do not use localized interacting fields and are therefore free of vacuum polarizations. In order to make some more specific remarks about these unitary and Poincaré-invariant models it is helpful to introduce some notation (the original notation, apart from Wick-products, which did not yet exist in the 40s) about these oldest S-matrix models

\[ S = e^{i\eta}, \quad \eta = \int \eta(x_1, \ldots, x_4) : A(x_1) \ldots A(x_4) : \, dx_1 \ldots dx_4 \] (3)

where \( A(x) \) is a scalar free field and \( \eta(...) \) is a connected Poincaré invariant function.

Unitary and Poincaré invariance are obvious whereas the validity of the cluster factorization property for asymptotic spacelike distances \( a \to \infty \)

\[ \lim_{a \to \infty} S |f_1, \ldots, f_k, g_1^a, \ldots, g_l^a\rangle = S |f_1, \ldots, f_k\rangle \otimes S |g_1, \ldots, g_l\rangle \]

follows from the connectness of the Poincaré invariant function \( \eta(...) \).

The spacelike clustering is the easy part of ”macrocausality”\(^4\). Stückelberg

\(^4\)The Heisenberg ansatz happens to fulfill this indispensable S-matrix property in an acci-
criticised Heisenberg’s approach on the lack of a timelike manifestation of macrocausality called "causal rescattering". The simplest illustration of this requirement is in terms of the 3 to 3 particle scattering which should contain as an asymptotic subprocess the scattering of first two particles and then at a much later time, the scattering of one of the outgoing particles with the third one. He showed that the asymptotic line which connects the two scattering events is described by (what was later called) the Feynman propagator at the value of an momentum which corresponds to the classical mass and velocity associated with the two events. This timelike asymptotic cascading structure, which must be contained in the S-matrix, together with the spacelike cluster-factorization, constitute the most important manifestation of macrocausality. This expression actually stands for all spacetime aspects which can be formulated in terms of particles only i.e. without the intervention of interpolating fields i.e. it does not include the crossing property of the S-matrix which cannot be understood without the microcausality-carrying fields.

Stückelberg used the asymptotic propagator expression for all distances and idealized the particle interaction region by a spacetime point. In this way he arrived prior to Feynman, but in a less legitimate way, to the Feynman rules. As a result it is almost impossible to answer the question: what did Stückelberg really intend with his criticism of Heisenberg? Did he want to point out that Heisenberg’s S-matrix setting is incomplete from the viewpoint of macrocausality or did he want to say that Heisenberg is barking up the wrong tree i.e. that a pure particle-based S-matrix approach is not the right way to counteract the ultraviolet catastrophe. The second view is probably the correct one because Stückelberg’s later contributions to QFT show that he wanted S-matrix ideas to be subservient to QFT. In principle he could have discovered an iterative construction of a unitary S-matrix by complementing his macrocausality requirement with an iterative unitarization. The analogy of Stückelberg’s S-matrix problem and the problem of unitarization of the dual model will be the issue which will be taken up later on.

This early S-matrix project moved out of sight for more than a decade, and a QFT liberated to a considerable degree from its ultraviolet divergence problem in the form of renormalized QED returned to the forefront. The crowning achievement up to the present time of this project of perturbative renormalization theory is the Standard Model. Although the SM only appeared on the scene after the failure of the second return of S-matrix theory in form of the S-matrix bootstrap, its concepts extended those underlying the pre S-matrix QED renormalization theory and had no connection with S-matrix ideas and the later string theory. The fact is that almost all the concepts of the SM were preempted in renormalized QED and enriched with important new computational technology; in this way the latter became part of the former. The return of S-matrix theory between the QED renormalization and the later S.M. had specific reasons. Since their understanding is important for our deconstruction.
project, we will check them out more carefully in the following.

In the 50s there was a giant step taken towards a better understanding between fields and particles. The omnipresence of localization-caused vacuum polarization made it desirable to understand better how particle concepts as the S-matrix, which are free of such vacuum polarization problems, can be reconciled with fields. The key to progress in that area was the formulation of the time-dependent LSZ scattering theory, the derivation of the reduction formalism and the foundation of both in localization and spectral (positive energy) requirements. In this way it became possible to derive properties of the S-Matrix which, unlike the aforementioned macrocausality, were genuine imprints of foundational properties of field theory. This opened the possibility of experimentally checking the foundational property of QFT namely the causal localization principle (micro-causal propagation) through the QFT adaptation of the optical Kramer-Kronig dispersion relation.

In this context a new basic structure linking fields with particles arose: the crossing property. It has its name from an obvious property of Feynman graphs: a contribution to say, two-particle scattering, has an intermediate one particle contribution which if viewed in the "crossed" channel looks like a process in which a particle is exchanged. But Feynman diagrams are on-shell (the mass-shell) and its not entirely trivial to show that there is an on-shell analyticity which allows to recast the graphical crossing into an analytic identity between a scattering process and its analytic continued crossed version. For the dispersion theorist the crossing for 2-2 particle scattering was sufficient, it was proven in [73]. For many decades this property was used outside the special established cases; most people considered it as self-evident. Only more recently with the advent of the of "modular localization" its conceptual subtlety (related to an extension of the KMS property) has been finally appreciated and its correct foundational position recognized [25].

The dispersion theoretical approach is the only successful concluded project in an S-matrix setting. It is in fact the only successfully finished project in particle theory: all its theoretical aims were achieved and experimentally verified, so that the individuals who have been involved in this project could turn towards other problems. Such a project would have lost its value if the structural properties (e.g. the Jost-Lehmann-Dyson representation) used in its derivation were based on guesswork and conjectures rather then mathematical proofs. This may have been the reason why Jost, Lehmann and Källén were so unhappy about the Mandelstam representation which has remained unproven and in retrospect defines the beginning of a more metaphoric discourse which led to the derailment of a large part of particle physics.

All the later S-matrix-based projects ended in a cascade of failures: the S-matrix bootstrap, the dual model and string theory. The common (but not the only) reason for the failures is the incorrect understanding of the meaning of crossing; on very recently the conceptual origin of the crossing property for form-factors (of which the S-matrix crossing is a consequence) was understood [23]. The bootstrap proposal was based on requirements which, as a result of their generality and vagueness did not have any constructive power. The belief that
one was in the possession of a unique particle theory namely a kind of theory of everything (without gravity) remained a grand fata morgana; instead of a theory of something it turned out to be a theory of anything in the worst possible meaning: each S-matrix derived from a QFT fulfills the bootstrap structure and as in d=1+1 one finds infinitely many explicit bootstrap solutions\(^6\) even within the family of factorizing theories (purely elastic S-matrices), every QFT in any spacetime dimension which has an S-matrix which fulfills Poincaré invariance, unitarity and crossing which are the defining properties of the bootstrap; so the bootstrap project, with the exception of factorizing models, was not wrong but empty.

The case of the dual model and string theory is much more concrete; as a result the misunderstanding and conceptual errors become more visible; it is our aim in this essay to expose them explicitly. This ends the constructive part of the essay which mainly serves to get better platform for the deconstruction of the conceptual basis of string theory.

The next section contains a critical evaluation of sociological and philosophical reactions to string theory. This is however not the kind of criticism supported by the author because it does not expose its scientific roots. A sociological and philosophical critique dangles in the void unless it is preceded by a scientific deconstruction. Certainly string theory and what its defenders write about it\(^6\) arouses in many people the feeling of looking at something bizarre, but it is not so easy to identify the scientific reasons from which these feeling emanates.

It is therefore not surprising that our analysis of string theory is preceded by a rejection of existing criticism of ST on the grounds that e.g. it did not lead to observational verifications. If a correct theory which is an extension of QFT does not lead to experimental verification this would be still sensational from a conceptual viewpoint since to supersede a highly consistent theory in a mathematical consistent way would be an incredible achievement. The greater problem is however to confront a conceptually wrong theory which over a long time agrees with observations (viz. phlogiston). Since we are claiming that ST belongs to the second kind, but up to now without observational agreement, we do not have to lose time on the first possibility.

The criticism starts in the third section in which the development of string theory from the dual model through the Nambu-Goto Lagrangian is critically analyzed from the viewpoint of localization which is central for all relativistic quantum theories.

As a contrapoint we explain in the fourth section the intrinsic meaning of string localization. After this constructive interlude we pass again to the destructive project in section 5 where the consistency of dimensional reduction (Klein-Kaluza) will be critically analyzed.

The metaphoric picture about particle theory in the wake of string theory is the topic of section 6, whereas section 7 analyses the impact of ST on the situation in Germany in the aftermath of LSZ, a topic of living history for the

\(^6\)This is not the result of the bootstrap setting but rather that of the factorization property together with the bootstrap, which has no counterpart in d=1+3.
author. The last section tries to counteract the belief that metaphor-based theories as string theory are the only "game in town".

3 The aim

...The history concludes with an unexpected and glorious success: the so-called standard model. The way in which this structural classification fell into place, and the great leaps of imagination involved, justifies a degree of hubris among the few dozens truly extraordinary individuals who discovered it. However both this hubris, and the complexity of the result, fed the temptation to go on leaping, and to forget that these earlier leaps, without exception, had taken off from some feature of the solid experimental facts laboriously gathered over the years....

Philip Anderson, in "Loose ends and Gordian knots of the string cult".

There is a widespread consensus among particle physicists that particle theory is in the midst of a crisis. Even string theorists, who feature in this statement of Phil Anderson as bearing responsibility for this situation, quite readily concede that particle theory has seen better times. They however propose a quite different remedy from that which would follow from Anderson’s diagnosis, namely they plead for the application of a stronger doses of the same medicine, because in their mind "there is no other game in town".

Anderson’s quite devastating indictment about nearly four decades of post standard model domination of particle physics by the noisy but scientifically unsuccessful ”string cult” expresses an opinion of an eminent condensed matter physicist which is shared by an increasing number of particle physicists.

Most of the criticism directed against string theory (ST) has been focussed towards its lack of observational success and more general the absence of any predictive power. Others are worried about the dominance ST has even outside of popular science. Indeed its metaphoric discourse about an alleged theory of everything (TOE) at universities and research institutions is a serious problem and concerns about its suffocating influence on other theoretical directions which are based on the less reductionistic ideas of a theory of something instead of a TOE are certainly well-founded. There are also those who are irritated by the strange philosophical opaqueness of ST. Meanwhile string theorists got used to this kind of sociological and philosophical criticism which does not reach the scientific foundations of their theory. On the other hand sociological ST-bashing has become an activity by which one can build a reputation, so that the survival of ST is not only important for string theorists but also to some of its critics.

It is noticeable that in all the sociological contributions the authors take a critical look at the dominant position of ST and explain very well the sociological reasons why younger people uncritically internalize its catechism. But they never explain why respectable older people, who are under no such career pressures (especially those who are the main string proselytizers mentioned before) believe

7As well known to every string theorist, this phrase was used by David Gross on several occasions.
in the validity of the theory. It is of course common practice to blame the foot-soldiers (in the present context, the young partisans of ST) and perhaps the propaganda division (as Brian Greens and others), but spare the generals; in this respect these critical contributions are not different from critique about many other human activities where critical pundits have become interested in the survival of target of their criticism, especially if their only fame or profile depends on its continued existence.

What has been totally missing is a conceptual criticism of the physical content of ST. If the string theorists view of their theory as extending QFT is correct, than this would be a remarkable achievement independent of whether nature realises it or not. One should not prematurely dismiss it on the grounds of problems it has in leading to observational test. Even if it contradicts observational facts, the mere observation that there is a consistent theoretical setting which extends QFT would be a remarkable feat which is bound to give new insights into the ongoing development of QFT itself. This would create a similar situation as the one which Einstein confronted with his purely theoretical discovery of General Relativity, when he thought about its possible observational failure as a lost chance for the Dear Lord. In the absence of observational support, the criticism of the theoretical consistency is the only aspect which really counts, and here Einstein was his own demanding critic.

In this note I will show that ST fails on two aspects. The first one is that the claim that a string is a string-localized object in spacetime comes from a misunderstanding of the intrinsic meaning of localization. Rather a string of ST is an infinite component field which represent a infinite mass/spin tower over one point and additional operators which transform between the levels of the towers. The misunderstanding about localization can be traced back to the dual model which shortly before its reformulation into the string theoretical setting was incorrectly interpreted as defining an embedding of a multicomponent chiral current "source" theory into the "target" space defined by its inner symmetry components; the metaphoric error consisted in attributing a string extension (a sheet in the graphical spacetime setting of Feynman) in target space to this object. But a relativistic quantum theory with causal localization cannot fulfill such an embedding idea: no lower dimensional theory can be embedded into a higher dimensional one; a spacetime which has to accommodate causally localized quantum matter (with the vacuum polarization caused by localization) is simply too holistic. When people have such ideas, they usually think about QM where this is possible. A chain of quantum mechanical oscillators can be placed anywhere (including into an internal space) since localization in QM, different from modular localization, is not an intrinsic concept. The only way of having 1-dimensional causally localized objects in higher dimensional spacetime is through string-localized covariant fields.

The claim that the inner symmetry acting on the components of the chiral current or rather its multicomponent potential in its exponential form (the operator presentation of the dual model) can be a noncompact group is surprising, since inner symmetry spaces in d>1+1 are known allow only compact group actions; and that the requirement of it being the Lorentz group which
together with positive energy translations leads to a finite number (connected by M-theory) of 10 parametric superstring representation involving fermionic degrees of freedom is even more remarkable, but nevertheless true. But why should a mathematical attention causing statement on a chiral model be the starting point for a new theory of spacetime? Isn’t the more logical procedure to look for special aspects of chiral theories which are known to admit different realizations of spin, statistics and inner symmetries (including noncompact structures in the case of irrational chiral models)?

From this first error resulted a second problem: how can that strange point-like embedding of a chiral model (the source) into the "target space" (the space spanned by its internal symmetry indices) be linked to Feynman rules for strings in terms of world-sheets (tubes) instead of world lines? Recipes for higher order scattering amplitudes were abstracted on the basis of such world sheet pictures which were interpreted as higher order approximations and up to second order explicit calculations were performed (perturbation in the genus in the geometric string setting). Whereas Feynman diagrams in QFT represent amplitudes in the operator/state setting of quantum theory, the conceptual status of the world-sheat rules for the interaction of an infinite component pointlike field remained mysterious. They become even more mysterious if, as will be shown later on, the "dual model" starting amplitudes are nothing else then the Mellin transforms of conformal QFT. A mysterious new connection of a particle S-matrix with a conformal QFT? Can unitarization recipes on a conceptually doubtful lowest order save the day?

The waiting for a consistent theory in which the tube rules represent the perturbation theory of an operationally defined problem (so that one can forget the unfortunate start from pointlike localized objects or the incorrect embedding picture which erroneously were misred as stringlike and start with the pictures) for almost 5 decades has had no success. No consistent formulation in terms of states and operators was ever found, even though it attracted the attention of the best minds in ST. The present situation is psychologically reminiscent of Samuel Beckett's "Waiting for Godot" where Godot stands for "quantum theoretical rules" i.e. rules in terms of states and operators as in Feynman's case which would give the graphical rules for splitting and combining tubes an operational meaning. In view of the fact that the zero order input in form of the Mellin transform (unlike a Fourier transform) has no autonomous operational meaning this looks like a "mission impossible". In this case the quantum theory associated with the worldsheet rules could have been taken as a start of a new theory, and the not very useful infinite component pointlike theory which is behind the source-target reading of the dual model or the canonical quantization of the bilinearized Nambu-Goto Lagrangian could have been ditched.

One can also see this situation of a missing quantum theoretical setting for the tube rules in a more antropomorphic manner as the reaction of particle theory against the imposition of an incorrect metaphor about localization which is the central theme of any relativistically causal QT.

Our presentation of the mathematical-conceptual flaws on which ST erected its claim of hegemony as a TOE may generate the impression that relativistic
quantum theory, after reaching such heights as QED, renormalization theory and the standard model, was suddenly taken over by a new generation of half-wits who rammed particle theory into the ground and in this way caused more than 4 decades of standstill. In order to avoid creating such an oversimplified and incorrect view it is necessary to present the scientific criticism in a historical context in which the different ideas leading to superST appeared. Understanding why whole communities made conceptual mistakes and took an erroneous path is as interesting and important as understanding what led to important discoveries, especially if these errors were made about the most subtle issue of localization which already led to many other misunderstandings unrelated to ST [60].

It would be very difficult to accomplish this without having lived through those times with an open critical eye. Recent historical accounts as [13] are of some help as long as one does not expect any critical viewpoint in a commemorative contribution.

Accepting that the dual model- and string-theorists were in no way less competent to their field theory predecessors, the question arises what was different after all, and why did a derailment of particle physics occur with them and not before?

There were at least two situations which could have caused an erroneous trend: the ultraviolet crisis which begun in the 30s and found its end at the time of the renormalization theory of QED of the late 40s, and the S-matrix bootstrap project which was supposed to lead from some S-matrix principles directly to a unique solution and which started in the late 50s and ended in late 60s around the time of the appearance of the standard model. The main difference to the situation which led to the modern ST is that the leading figures before the dominance of ST (starting in the beginning of the 80s) were much more aware of the importance of balancing the speculative aspects of particle theory with a critical analysis which goes to the bottom of its conceptual structure.

The discovery of a theory which generalizes quantum field theory (QFT) not only on formal grounds but also on a conceptual level would of course have been a remarkable achievement. Most attempts over 5 decades to supersede QFT, be it through nonlocal/noncommutative changes or a pure S-matrix theory have ended without useful conclusions, but not as a result of an conceptual-mathematical inconsistency. ST is a special case; it is the only project for which one can pinpoint to a conceptual error at the most important concept which devides relativistic quantum mechanics from relativistic theories which have a causal propagation at all distances (sections 4-7). This is the central issue of localization which devides QM and QFT/ST more than any other property: Born-Newton-Wigner localization for QM and and modular localization for causally propagating theories (QFT, ST).

All the other sociological or philosophical arguments given against ST are secondary, even the question whether ST during its 5 decades of existence has explained any observed phenomenon. There is no time limit on exploration of deep ideas beyond QFT, but the question is whether the 5 decades old ST represents such a consistent extrapolation. Even if such a theory is mathematically too complex to make new predictions or if a prediction comes into contradic-
tion with observations, it is still important to pursue its consequences; the mere existence of a conceptually consistent theory which contains QFT as a limiting case requires this. An experiment can decide whether a theory is useful or not, but not whether it is consistent as a conceptual-mathematical construct and whether it can be viewed as an extension of an established theory and from the old phlogiston theory of burning we know that a theory can explain phenomena and make prediction and yet be wrong.

A historical illustration about the importance of inclusive consistency is Einstein’s reaction when the gravitational deflection of light on the sun was observed and he exclaimed that in the case of a negative result the Dear Lord would have missed an interesting chance. The history of ST proceeded quite differently, the theory had to undergo several metamorphoses passing through real laboratory particle physics before ending at the secure Planck length and bringing tenure to one of the protagonists, before the ST community placed it at the center of a new ultrareductionist TOE.

The concrete illustration of how ST was able to introduce misleading metaphors into particle physics, and disturb the equilibrium between innovative speculative ideas and their critical assessment, will be the main aim of this essay. As regards to sociological aspects of the crisis, I will stay within the boundaries of my personal experience and focus on how ST was able to get a foothold in German particle physics.

The central metaphor of string theorists, based on the form of the classical Nambu-Goto Lagrangian \[14\][15] which describes classical strings, is the credo that ST has to do with quantum objects which are string-like localized in space-time. It may be expected that its verification is not an easy matter since the concept of quantum localization is not only the most subtle in QT, but there is also a big distinction between localization in QM which is best be expressed in terms of wave functions on the spectrum of a position operator and the modular localization\(^9\) of quantum theories with a finite propagation speed at finite distances as causal relativistic theories.

The conceptual differences are considerable: from a mathematical viewpoint localized algebras in QM are von Neumann factors of type I, together with the complementary localized algebra they tensor factorize which leads to the notion of entanglement and the connected rich information theoretical concepts \[60\]. On the other hand the local subalgebras in a theory with modular localization are factors of hyperfinite type \(III_1\) with very different physical manifestations in that that there is no tensor-factorization for causal subalgebras with respect to their causal disjoint because the vacuum polarization at sharp localization boundaries prevents this.

Even if one creates a split distance \(\varepsilon\) between the two which tames the

\(^8\)We follow time-honored traditions of respecting well-established terminology even in case when new findings show that the chosen name is metaphoric and without an autonomous significance.

\(^9\)This is the the causal localization (spacelike commutance of observables and their causal timelike determination in the causal shadow region) but formulated independent of "field-coordinatizations".
vacuum polarization and generates a fuzzy localized type I intermediate factor which can be used for tensor-factorization, the restriction of the vacuum to this tensor-factor is a thermal KMS state which gives rise to localization entropy \[S_0\]. Actually causally localizable theories have both: the frame-dependent BNW localization coming with the Born probability and covariant modular localization mainly for the operators. Both approach each other asymptotically in the scattering limit of large times which is absolutely crucial for the correct understanding of the particle-field relation.

Rephrased in a way which does not refer explicitly to quantization of classical data, the ST credo relies on the possibility of embedding a chiral conformal field theory as a stringlike subtheory of a higher dimensional relativistic theory whose living space is referred as the target space. In contrast to the totally vague and useless general bootstrap project, the stringy object is very specific: it is a model in a 10 dimensional dimensional spacetime. As in standard QFT in curved space-time to each CST there is another (or many) reference state which is as similar as possible to the Minkowski vacuum.

But the story of the source-target embedding is a fairy tale, since in contrast to QM, where one can place a chain of quantum oscillators anywhere, it is not possible to do this in theories with a causal localization. The spacetime and the quantum matter in it are too holistic as the result of the omnipresence of vacuum polarization from localization. Even in doing the opposite, namely restricting such a theory to a lower dimensional spacetime (brane) there is a problem\[10\], although it can be done, the brane theory exists mathematically but not physically. A similar problem is encountered with the Kaluza-Klein compactification.

The impact of these statements on actual calculations are easily seen in concrete cases; in both cases, the canonical quantization of the Nambu-Goto model and the dual model embedding of the chiral current theory (the operator representation of the dual model) both lead to pointlike structure. The infinitely many oscillators do not lead to a stringy extension in spacetime because they enrich the internal Hilbert space over a point in a similar way as the spin components.

One could of course dispose of localization aspects of dual models and string models and directly ask whether the unitarization prescriptions for a tentative string S-matrix which the string theorists came up with are consistent and whether they justify the name "stringy". The first question is clearly defined; one must show that the recipe can be formulated in terms of operators and states. This is a problem which through all the S-matrix history was never solved for any theory. The most famous attempt was that of Stueckelberg mentioned previously. Unless one knows already that there is an off-shell operator theory behind, there is no chance to guess one. Despite more than 30 year research on this problem, including the most experienced individuals as Witten, all these\[10\]It is however perfectly normal to have together with pointlike fields also semiinfinite stringlike localized field \[\psi(x,e)\] in a theory (see section 7). Fields carrying a Maxwell charge are of this kind where Field strengths remain pointlike. Stringlike fields, despite their intuitive proximity having nothing to do with source-target image.
attempts have been in vain.

The second problem, the stringyness of an $S$-matrix, seems to be a contradictory requirement. To the extent that "stringyness" is a spacetime notion (what else can it be) the correct question is: how does off-shell stringyness manifest itself on-shell? The best example of a field which cannot be point-localized, but whose best possible localization is semiinfinite string-like, is a Dirac particle which carries a Maxwell charge. In that case the LSZ limits vanish and as a result of perturbative infrared divergences also the perturbative $S$-matrix is ill-defined. The inclusive cross section with finite photon resolution is finite but one can neither abstract an $S$-matrix nor relate it to a spacetime limiting process. A stringy $S$-matrix is simply slippery a notion.

In the next section it will be shown that the quantum counterpart of the classical Nambu-Goto string (or its supersymmetric extension) describes higher dimensional infinite component pointlike wave functions which can be associated with infinite component free fields i.e. the *mass/spin tower sits over one point and is not carried by a spacetime string*. The recipes about splitting and recombing of tube by which string theorists assign a "would be" $S$-matrix, constitute an ad hoc attempt to use the (as it turns out incorrect) metaphor of strings in spacetime in order to assign transition probabilities between infinite component wave functions. Short of a large time limit process by which the interacting operators are connected with the in- and out-going free particle configurations, string theorists do not derive the $S$-matrix from local quantum physics but rather *defines* it by assigning transition amplitudes to interaction-free wave functions with the help of tube pictures, which are then translated into analytic formulas (taking some inspiration from Feynman rules). So in QFT the $S$-matrix is derived whereas in ST it is postulate.

The unraveling of the string metaphor will be the principle aim of the next section. In the third section the string theorists incorrect idea about localization in relativistically covariant theories will be retracted to the very beginning of ST namely to the Veneziano-Virasoro-Dolen-Horn-Schmidt duality and its interpretation in terms of an alleged string-like embedding of a special chiral conformal QFT into the physical spacetime. For a previous more detailed description of string theories historical roots we refer to [9]

At the root of these metaphoric disorientation there is a widespread fundamental misunderstandings of the concept of causal localization. Therefore section 5 is a reminder of "modular localization" (causal localization of QFT after liberating it from the fortuitous field coordinatizations). Although modular localization has rich group theoretical and geometric aspects and is certainly quite deep as a mathematical theory with strong relations to operator algebras, it has little relation to the kind of differential geometry and topology in particle physics as used particularly in gauge theory as it enjoyed popularity starting in the 70s. We will give several illustrations which show that certain geometric interpretations are not supported by intrinsic localization properties[11].

\[11\] A prior critical account similar to the present one, but which more emphasis on the sociological aspects of the present crisis can be found in [9].
In section 6 we will show that some ideas which originated from ST (but which afterwards developed a life of their own), as extra dimensions, have to be taken with a grain of salt. The only way they start to make physical sense is if an operational meaning can be attached. It will be shown that the high temperature limit coupled with the operational connection between real and imaginary time local operator algebra is the necessary prerequisite for a dimensional reduction which maintains the Hilbert space setting and the positive energy condition of the 10 dimensional superstring. A quantum generalization of the classical Kaluza-Klein setting which is consistent with local quantum physics remains uncharted territory.

It is indicative that foundational work on QT which has been able to incorporate even the counter-intuitive structure related to the quantum reality has capitulated vis-a-vis ST. A framework of principles as it is available for QM or QFT does not exist for ST, it would not make much sense in a theory which claims to be a TOE. Who gets involved with ST and asks for conceptual guidelines has to be prepared to confront the surreal. A presentation of a theory as a realization of physical principles is only possible after a theory has been known beyond its metaphors. For a theory as ST, for which its main thesis, namely that it deals with string-localized objects in spacetime, turns out to be a metaphoric illusion, any foundational placement which overlooks this fact would be illusory.

Metaphoric ideas around a new theory are sometimes quite helpful, as long as one conscientiously uses them as temporary placeholders for not yet precisely understood facts. The complementarity principle and the uncertainty relation of QM which later were derived from noncommuting operators are examples of such a positive transitory role in particular at the beginning of a new theory. However the situation of the string metaphor in ST is quite different. It is a misleading metaphor which is still believed by all members of the string community and even most particle physicists outside who do not find it useful.

The string oscillators are not objects in spacetime but are part of the internal space. In particular the quantum object corresponding to the classical Nambu-Goto string is an infinite component wave function respectively an infinite component free field describing a mass/spin tower over one point in spacetime. The search for infinite component fields (in analogy to the group theoretical $SO(4, 2)$ construction of the hydrogen spectrum) which could produce an interesting particle spectrum without having to go through tedious dynamical computations, was a popular research topic a decade before ST, but it remained without success.

The existence of the solution of the quantum N-G model shows that such infinite component objects do arise (but only in 10 dimensions) if one uses instead quantum oscillators as they arise from the Fourier decomposition of closed/open strings. The oscillator degrees of freedom (respectively their supersymmetric counterparts) set the mass/spin tower as well as their relative strength in the infinite component wave function; but this has nothing to do with extended objects in spacetime. String theorists were so spellbound by their mind games, that up to this date they did not realize that even though their construction has
nothing to do with spacetime strings, it did solve the older problem of infinite component wave equations, which apart from the high dimensions probably would have pleased their older predecessors of the infinite component project.

The present attempt of "deconstruction" of ST (in its contemporary philosophical use it means subjecting something to critical analysis by carrying it to the breaking point) is an attempt to fill this gap. Given the present Zeitgeist in particle theory it is not very probable that this nor any other criticism of the dominance of metaphoric arguments in particle theory will have any short range effect, but it may facilitate the task of historians of physics to understand what happened to the millennium project of a TOE.

4 A critical review: from the dual model through the Nambu-Goto model to the superstring

In this section we will show that ST does not describe string-like extended object in spacetime, but rather constitutes a construction of nontrivial models of infinite component wave functions. It is well known that infinite component generating (distribution-valued) covariant wave functions are in a one-to one relation to multi-component free fields. In case the reducible unitary representation of the covering of the Poincaré group has no irreducible components which fall into the class of Wigner's "infinite component massless representations" (see next section) both the generating wave functions as well as their quantum field counterparts are pointlike localized objects. By an infinite component field one does not simply mean a direct sum of free fields. The theory should contain operators which "communicate" between the different levels of the infinite mass/spin tower over one point in the sense that they do not commute with the mass operator; if this would not be the case, there would be no mechanism by which one could generate a "dynamical" spectrum and the concept of infinite dimensional fields would be without physical content.

It is precisely in this dynamical sense that the terminology "infinite component fields" entered the discussion some years before ST was proposed. Attempts to work with infinite component wave functions date back to Majorana; in the early 60s they underwent a revival. The increasing particle zoo made it seem advisable to look for "dynamical symmetries" which generate a rich mass/spin spectrum in analogy to the spectrum-fixing SO(4,2) symmetry for the hydrogen atom; the problem of how this can be reconciled with a Lagrangian picture of interactions was deferred to after a successful construction. These attempts where all based on noncompact groups containing the Lorentz groups. This project remained without success and was soon suspended.

More interesting possibilities arise if one goes outside noncompact groups and permits a full quantum mechanics or more generally a chiral conformal

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12 Since the objects are distribution-valued, this needs an appropriate mathematical formulation.

13 The guiding principle was to emulate the O(4,2) description of the hydrogen spectrum (Barut-Kleinert, Ruegg, Fronsdal, Budini,...) in the covariant relativistic context.

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field theory at its place. Although this is not the way string theorists see their subject, it is the best metaphor-free way to approach it.

Instead of using the above structural argument which says that every representation space of a unitary ray representation of the Poincaré group not containing massless infinite spin components is necessarily pointlike, it is more revealing to use the pedestrian method of quantizing the bilinearized Nambu-Goto string Lagrangian. A mathematical physics presentation can be found in [18] and less rigorous but still correct computations have been presented before in articles written by string theorists [22][21].

Leaving temporarily the physical interpretation aside, one may ask the mathematical question whether there exist quantum mechanical models which, attached to a localization point in a particular way, leads to an infinite component local free field with a nontrivial mass/spin tower. Since such free fields are characterized by their (graded) commutator functions it is easy to see that the problem of local field is equivalent to the construction of an infinite component wave function. The infinite component one-particle Hilbert space of such a model must be a subspace in a tensor product

$$H_{sub} \subset H = L^2(p, \rho(\kappa^2))d\kappa^2 \frac{d^{D-1}p}{\sqrt{p^2 + \kappa^2}} \otimes H_{QM}$$

where, in order to obtain a unitary representation of the covering of Poincare group with a spin spectrum (the first factor is scalar) the operators in $H_{QM}$ must have a vectorial/spinorial multiplicity index i.e. they must be vector or dotted/undotted spinor-valued.

At this point the setting is completely general and does even contain the generating wave functions of so called generalized free fields (having a continuous mass spectrum). In particular the Wigner representation theory of irreducible positive energy representations is of this form. In order to describe a massive $s=1$ vector representation one starts from $H_{QM} = \mathbb{R}^4$ with the generating 4 component unit vectors and sets $\rho(\kappa^2) = \delta(\kappa^2 - m^2)$. The invariant metric is always indefinite at the start, reflecting the fact that finite dimensional vectorial/spinorial representations are not unitary. The construction of a unitary subrepresentation is done with the help of intertwiners i.e. vector/spinor valued functions $u(p, s), s =$physical spin (and their charge conjugate $v(p, s)$) which project the formal tensor-factorized states in $\mathcal{H}$ into $H_{sub}$ [14]. For $D=4$ and $\text{dim}H_{QM} = 4$ one obtains the $s=1$ representation in the vector potential description which fulfills the Klein-Gordon as well as the vanishing divergence equation. A generalization to reducible representations with several masses and spin would be unproductive unless one finds a dynamical mechanism which generates a specific mass/spin spectrum. Such a mechanism must provide additional operators which connect the different irreducible levels and taken together with the Poincaré generators act irreducibly on $H_{sub}$.

This was the idea behind the infinite component field projects in the beginning of the 60s [20]. Those authors tried to implement it with the help of group

\[14\] This procedure is described in the first volume of Weinberg's book [19].
theory by extending the Lorentz group to a larger noncompact group and by looking for unitary representations of these groups. This turned out to be a blind alley and the idea was given up after 5 years. The main issue of this section is to point out that the project is successful with infinitely many vector/spinor valued oscillators as they arise as Fourier components from $D$-component abelian chiral currents on a circle and its unique result is the 10 dim. superstring. The terminology "string" for the resulting pointlike infinite component field is the most unfortunate terminology in the history of particle physics.

Some renown physicists lend support to ST but had some second thoughts on the issue of localization. Steven Weinberg thought the ultimate irony is if ST would turn out to be equivalent to some unusual model of QFT. The dynamical infinite component field called 10-dimensional superstring is indeed a pointlike object and therefore answers Weinberg’s ironical question.

If one ignores the positivity of energy requirement one finds another solution with $D=26$ which is somewhat simpler to present: the bosonic Nambu-Goto model. One starts with the oscillators of a quantum mechanical string and defines as $H_{QM}$ the Hilbert space generated by the n-component oscillator Fourier coefficients leaving out the n-component zero mode which is identified with the D-dimensional momentum $p$ of the first tensor factor. In this case the construction of the positive definite subspace in which the Poincaré representation becomes unitary is more subtle then in the Wigner case massive particles or massless representations with finite helicity. The trick which leads to simplification consists in remembering that the original nonlinear formulation of Nambu-Goto was reparametrization invariant, which in turn leads to subsidiary conditions on the oscillator Fourier components. Their use leads for $D=26$ to a subspace without negative norm states which still contains null-states. The remaining canonical step consists in “dividing out” null-states. Allowing spinorial valued oscillator Fourier component one can remove the last flaw namely the absence of energy positivity and one arrives at the $D=10$ superstring.

Admittedly this aspect of uniqueness is somewhat astonishing. But is it sufficient reason for claiming a new era of understanding about spacetime? Definitely not, as will become clearer in the sequel the solution must be looked for in peculiar properties of inner symmetries of chiral models; under special circumstances their inner symmetry space can support a Poincaré group symmetry. This will become more explicit in the setting of the dual model below.

All these calculation have been done a long time ago but there is a kind of schizophrenic gap between the correct calculation leading to the pointlike nature of the resulting infinite component field on the one hand and the metaphoric claim that the objects are extended "wiggling little strings" (with the occasional admission that they are "invisible" apart from a point). Not wanting to interrupt our presentation of ST and the dual model by sociological explanations we desist from further comments.

For a scientific (partial) understanding of what may have been on the mind

15The DHR superselection sector theory derived from representation theory of local observables leads to compact internal symmetry groups for $D \geq 4$ but does exclude noncompact ("nonrational") structures in chiral models.
of obviously intelligent young particle physicists it is necessary to look at ST’s predecessor which is the dual model. This model as well as its ST extension is a concrete model with explicitly given computational rules which emerged from the legacy of the more abstract setting of the S-matrix bootstrap. The latter was a framework of which the strong interactions (actually described by QCD) were thought to be the unique solution. The S-matrix bootstrap had incorporated one property which was missing in previous S-matrix attempts namely the crossing property for scattering amplitudes. This is perhaps the most subtle property in QFT concerning the particle-field relation, and it is certainly not our intention to go in detail into its conceptual setting for which we refer to [25].

In order to get a better understanding of crossing, Mandelstam proposed a spectral representation for the elastic two particle scattering amplitude; but neither did the understanding of crossing as a consequence of first principles improve from it, nor was it possible to add the Mandelstam representation to the various other rigorously derived spectral representations which one was able to derive from the principles of QFT. It did however play an important role in Veneziano’s discovery of the dual model, which was followed with extensions and improvements by several other particle physicists [13]. The physical motivation was purely phenomenological (related to Regge trajectories); it was soon forgotten after new experiments disposed of it. But the mathematical attraction of Veneziano’s profound appearing observation on the basis of pedestrian methods exerted a quite irresistible pull for many workers. To many it looked like a deep observation whose physical realization still had to be found.

The first operational presentation of the dual model arose in collaboration of Fubini with various collaborators [26]. Using the terminology of chiral quantum field theory they showed how one can obtain the dual model from a multi-component abelian chiral current. The important objects in this construction are not the d-component currents themselves but rather the exponential of their potentials.

\[
\left[ j_k(x), j_l(y) \right] = -\delta'(x - y)\delta_{kl}, \quad Q_k = \int j_k(x)dx, \quad \Phi_k(x) = \int j_k(x)dx \quad (5)
\]

\[
\psi_\alpha(x) = \left. e^{i\alpha \cdot \Phi(x)} \right| \rightarrow V(z, p) = e^{iP \cdot X(z)} \quad (6)
\]

In the QFT setting the d-component vector \( \alpha \) in the exponential of the d-component potential \( \Phi_k(x) \) is the multi-component charge carried by the field \( \psi_\alpha(x) \) which applied to the vacuum generates a state in a new representation sector for the current algebras. Since the \( \alpha \) spectrum is continuous, there is a non denumerable number of superselection sectors and the direct integral Hilbert space is nonseperable. The indicator for the emergence of new superselection sectors above the vacuum sector is the infrared divergence\(^\text{16}\) in the integral

\(^\text{16}\)Infrared divergencies cannot be handled by renormalization theory, their appearance points to basic physical changes, in the case at hand that the charged fields \( \psi \) are not composite fields in the current in the vacuum sector.
representing the potential. The first time this problem arose in QFT was in a paper by Pacual Jordan entitled "the neutrino theory of light" which caused quite a confusion because in reality it was about chiral bosonization and re-fermionization which in the setting of states (Jordan only used commutators) shows the mentioned infrared problem [27].

The mathematically and conceptional clearest presentation for a one component current theory can be found in [28]. If one wants to use chiral models as a theoretical laboratory it is more interesting to convert this "non-rational" chiral theory into a "rational" model; this done by enlarging the algebra by declaring certain (those which commute for finite distances) as members of the enlarged observable algebra. The maximally extended observable algebras can be classified and are "rational" i.e., have a finite number of charge sectors [28]. This method can be extended to multi-component currents [29][30] where the maximal extended observables are classified by even lattices and their superselected charge sectors correspond to their dual lattices. The list of models contains some examples of high mathematical attraction related to finite exceptional groups the moonshine.

Having spent some time on the QFT use of multi-component chiral current models makes it easier to appreciate the way the dual model uses the multi-current model. In that case the use of this formalism for setting up an operator version is slightly different. By declaring the null-mode of the chiral conformal potential to define an d-component quantum mechanics the infrared divergence is removed and its exponential function is now acting in the quantum mechanically extended vacuum sector which is the only one i.e. the superselection structure including its maximal extension has been lost. One now has the following re-interpretation

\[ \alpha \rightarrow p, \quad \dim \psi_\alpha = \alpha^2 \rightarrow m^2 \]

(7)

The d-component charge passes to the d-component particle momentum and the dimension of the charge-carrying field goes to one of the masses in the mass/spin tower of the dual model. The loss of the continuum of superselection sectors is in accord with the fact that momenta can be superimposed.

In fact Mack’s observation [31] that any conformal theory in any spacetime dimension always leads (through is Mellin transform) to a dual model in the sense of a meromorphic function of Mandelstam variables with a pole structure of a dual model with the correct factorization of the residua coming from the locality of the conformal theory. Mack’s most astonishing result is based on the fact that the cause for the appearance of ”particle poles” in the Mellin transform is the Euclidean conformal operator product expansion (OPE [17], which is a partially resummed Wilson expansion. It has its rigorous backup in the conformal partial wave expansion which also establishes its convergence.

\[ \text{As a result of the covering structure of the physical conformal group, the global conformal operator expansions in real time are more subtle than their euclidean counterpart [32], they lead in fact to the conformal block decompositions which reveal an algebraic commutation structure in the timelike Huygens region which replaces the commutativity of observables.} \]
In more detail, the correct dual model factorization of the residua of the particle poles in the Mellin transformed correlation function arises from the conformal operator product expansion inside a conformal correlation function. Mack shows that one can also use the dual model properties in order to define a conformal QFT; in this inversion that fact that the field theoretic positivity simplifies (only two-point function of fields have to be positive) due to the validity of OPE is important. He also stresses that the dual model does not depend on the spacetime dimension of the conformal QFT from which it was constructed. On the other hand the recent proof of the crossing property has shown that the latter has a completely different origin in which scattering theory and not conformal structures play the main role.

After the experimental situation went against Regge phenomenology and its sophisticated extension by the dual model, the correspondence between dual models and CFT via Mellin transformation also removed a good part of the mathematical mystery. It will be shown later on the crossing property of scattering amplitudes and formfactors in QFT has a totally different conceptual origin than the duality of the dual model in particular duality is not a special of the crossing property.

Whereas higher dimensional CFTs leads via the Mellin formalism to the duality relations in terms of Mandelstam variable, it does not possess the d-component continuous charge $\alpha$ of chiral current models which in the operator presentation of the dual model is re-interpreted as the momentum $p$. Although this is not needed from the strict dual model viewpoint, the requirement of "charge turning into momentum" is essential for the transition to ST. For this passage one needs to construct a unitary positive energy representation of the covering of the Poincaré group and, as in Wigner’s approach one needs an momentum space. The only step which causes a major conceptual headache is the use of an inner symmetry space defined by the charge components of a chiral current model. The reason is that the quantum origin of inner symmetries, which finally was understood thanks to the Doplicher-Haag-Roberts theory of superselection sectors [1], had revealed that there exist only countably many superselection sectors on an observable algebra and the associated symmetries are described by the action of compact groups on the indices of fields.

The theorem excluding noncompact inner symmetry structures does not hold in chiral conformal theories, and existence of the current model with its continuous charge spectrum shows that. On the other hand all the interesting chiral models (minimal models,...) have a compact internal structure in the sense that they are rational (finite number of sectors), unlike the current model which in this terminology would be "irrational". But the uncountable nature of the charge sectors does not mean that (returning to the case at hand) one can find a subspace on the linear space of all real charges on which a unitary positive energy representation of the Poincaré can act. If somebody would have asked me to bet on this, my answer would have been that there is no chance. Well, statistically I would have been right because there is precisely one case which I would have overlooked: the $d=10$ superstring, which belongs to a representation in which the chiral current has also spinorial indices in addition to vectorial
The world of chiral CFT is full of surprises and one has to except that there is a chiral objects whose internal symmetry structure mimics 10-dimensional spacetime behavior. But should one turn a chiral mimicry into a metaphor for a 10 dimensional living space which then becomes the starting point of curling away unwanted dimensions in order to explain our living space? All the properties discovered in ST, i.e. the finitely many different versions of the 10 dim. superstring and the possible interrelation by the big Latin letter M are clearly properties of a particular multicomponent chiral current model and should be understood right there. To draw conclusions about physical spacetime in the form of "M theory" carries particle physics into the muddy water of metaphors and a kind of new age particle physics in that one cannot prove that it is wrong, but one does not have the impression that it can right either.

But there is one aspect which actually led to a wrong conclusion. This is the claim that chiral theory associated with a multicomponent current can be used to define an embedding of the chiral current theory (the source theory) into the 10 dimensional inner symmetry space re-interpreted as a unitary positive energy representation space of the covering of the Poincaré group (the target space) defines a string in target space (an extended string-localized object). This metaphoric but unfortunately incorrect idea results from picturing the embedding as a map of the 1-dim. chiral theory into a 1-dim. object geometrically embedded into the 10 dim. target space. What really happens is that apart from the zero mode, the oscillator degrees of freedom resulting from the Fourier decomposition of the chiral conformal QFT in the circular compactification form the infinite components of

The remaining problem is to characterize such a subspace. But this is precisely what the $u$-intertwiner accomplish.

In the case of the infinite dimensional setting of the N-G model there two conditions which these oscillators have to obey: the string boundary conditions and the reparametrization invariance condition. The corresponding quantum requirements are well-known. In the present tensor product setting they mix the momentum of the sought object with its "internal" quantum mechanical degrees of freedom and in this way one gets to the physical states. The two conditions provide the additional knowledge for a master-intertwiner which intertwines between the original covariant transformation law and a positive metric subspace $H_{sub}$ on which the representation is semi-unitary. As mentioned the formation of a factor space $H_{sub}$ leads to a bona fide unitary representation.

Since all unitary representations are completely reducible and a free field in a positive energy representation is fully determined by its two-point function, it is clear that the resulting object is an infinite components pointlike field and not a string in physical spacetime. The string has not disappeared, but contrary to naive expectations it did not become embedded in spacetime but rather is encoded into the mass/spin spectrum as well as in the irreducible component $u^{(AB,s)}$ intertwiners. (more below).

If one wants to cling to a geometric picture of a string, it should be a "ver-
tical" string in the highly reducible "little Hilbert space" which is the inner
Hilbert space over each point on which the oscillator variables act. Those trans-
formations in the oscillator space $H_{QM}$ which leave the subspace invariant and
do not implement Poincaré transformation, mix the irreducible components of
the infinite component field. This corresponds to the "wiggling" of the "inner"
string, a totally unphysical process which corresponds to the flipping of the
masses and spins between different multiplets. It is not the string in spacetime
which wiggles but rather the particles in the tower over one spacetime point; they
wiggle in the sense as the oscillator interpretation of pointlike fields always
did to those who think that this is an appropriate visualization of free fields.

There is full agreement with the computation in the cited papers, but there is
also total disagreement if it comes to interpretation. Whereas for string theorists
it is a spacetime-embedded string of which only its center of mass is visible, our
derivation shows that it is really the construction of an infinite component wave
function and the localization point is not the center of mass of anything.

Results of calculations often need the help of interpretation. The most fa-
mous illustration is the Lorentz-Einstein disagreement in the interpretation of
the formula for the Lorentz interpretations with Einstein’s radical ether elim-
nating proposal coming out as favoured by nature. Since ST originated as a
mind game, there does not seem to be any role for nature to play. But in both
cases the correct interpretation is selected by the application of Ockham’s ra-
zor; in the ether-relativity interpretation it is the superfluous invisible ether,
whereas in ST the invisible string which has to conk out.

Another comparison within quantum theory designed to highlight the mag-
nitude of the conceptual disaster is to create an analogy between the illusionary
invisible strings and a (hypothetical) attempt to attribute a position as well as
a momentum on the basis of the integrand in Feynman’s path integral. This
actually may have happened if Feynman’s path integral representation would
have been discovered before Heisenberg’s matrix mechanics. The nonexistence
of a material string in spacetime has its exact counterpart in the impossibility
to embed a chiral conformal field theory as a stringy-localized subalgebra into a
higher dimensional spacetime in such a way that the latter is the "target space"
of the former. This was actually the interpretation of the dual resonance model
before it became re-packed into the Lagrangian setting of ST. The target space
interpretation with extra dimensions only generates the spacetime dimension
but does not embed the chiral theory into this target space. Analogous to the
spin degrees of freedom the degrees of the chiral theory go into the "inner"
Hilbert space over each spacetime point and there is no physical interaction
which is capable of transforming this into a spacetime string.

The above argument about the canonically quantized bilinear bosonic Nambu-
Goto Lagrangian has an analog for the various 10-dimensional superstrings. The
main difference to the Nambu-Goto case is the undotted/dotted spinorial val-
uedness of the oscillator variables which replaces the vector valuedness.

Staying for a moment with the chiral embedding picture of ST, it is interest-
ing to note that this way of looking at ST helps to lend plausibility to restriction
of the embedding construction to 26 respectively 10 spacetime dimensions. The
target space of the chiral conformal field theory is (by definition) the finite dimensional vector/spinor valued index space of the multicomponent conformal current (whose circular Fourier decomposition lead to the oscillators). With other words the target space is a visualization of the internal symmetry space of the source theory. In higher dimensional QFT the nature of internal symmetries can be derived from the localization structure of the observables \[1\]. The DHR theory, which leads to compact group symmetries, is however not valid in \(d=1+1\) so one should be prepared for exceptions with noncompact inner symmetries. The fact that within the family of chiral current models this only occurs with 26 respectively 10 supersymmetric components leading to \(d=25+1\) and \(d=9+1\) Lorentz symmetry in target space has to be proven. The intuitive argument only reveals that its existence goes against naive expectations. This stands out against two other facts which harmonize with naive expectations, genuine spacetime strings exist in every dimension \(d > 1 + 2\) (see next section) and a more intrinsic quantization of the Nambu-Goto string (in the original square root formulation) which is based on the fact that this system is completely integrable \[74\] also does not lead to restrictions of spacetime dimensions. It is only the string theorists strange use of this Lagrangian as a vehicle to generate spacetime from the inner symmetry of a multicomponent chiral current (the infinite oscillators on a circle) which leads to this restriction. This picture and its consequences is identical to the source-target embedding of its dual model predecessor. A positive energy representation of the Nambu-Goto algebra in a Hilbert space is indeed unique and equal to the 10-dimensional superstring representation, just as the string theorists claim, but it is point- and not string-like. One can even be surprised about the uniqueness of the answer to the target space interpretation because the general expectation is that the inner symmetry space of a QFT cannot be the localization spacetime of a higher dimensional QFT\[18\], but this theorem does not hold in chiral theories. Although there is no proof that in chiral theories one cannot represent a noncompact group as the Poincaré group the one and only one case of the pointlike infinite component superstring field is the only known counterexample. The problems starts if one wants to transfigure the component space of a chiral model into our living spacetime after descending from 10 to 4 dimensions by "curling up" 6 of the spatial dimension\[19\].

Comments about the introduction of adding interactions to infinite component wave functions will be deferred to later.

The formula just describes the most general pointlike field in \(d=1+3\). There are corresponding formulas for every dimension but the number of Casimir invariants increase with increasing spacetime dimensions for both the massive as well as the massless components. Both, the unitary representation of the Nambu-Goto string as well as its supersymmetric analog are pointlike \[18\]; in fact a unitary representation of the covering of the Poincare group which does

\[18\] In dimension \(> 2+1\) there is a theorem that the inner symmetry space of a QFT is always the representation space of a compact group \[62\].

\[19\] The curling up generates a problem of its own: it does not get rid of the degrees of freedom which are by far too many for a physical 4-dimensional QFT.
not contain an irreducible infinite spin component is automatically pointlike generated and this is inherited by the associated free field. The application of the oscillator algebra to a pointlike string state leaves it pointlike but changes the system of c-parameters i.e. the application of the oscillator algebra does not change the localization but modifies the relative admixture of component contributions beyond what is already done by the action of the Lorentz group.

The question of whether all admissible pairs \((A, \dot{B}; s)\) occur, and if not which ones do appear can only be settled by a more detailed computation which for obvious reasons we are not prepared to do since neither infinite component wave functions nor its ST metaphor justify such additional work.

An infinite component free field theory is still a QFT and hence the introduction of interactions should follow the standard logic of coupling pointlike fields. But instead the rules to deal with interactions rely on the metaphor of a spacetime extended string. Indeed, the graphical tube rules, which define the ST interaction as a string-like analog of the Feynman rules for point-like objects, only make physical-intuitive sense for genuine spacetime strings. With this not being the case, the tube rules lose their physical support and the question arises whether the transition matrix elements calculated according to those metaphoric rules fulfill the physical properties of an S-matrix of particle scattering, as unitarity and macrocausality [9]. In the case of Feynman rules this is possible even without using an operator description. For the tube rules this has not been done; there exists not even a credible perturbative (in the genus associated with the combining and splitting tubes) proof of unitarity.

The senseless metaphor of a spacetime string together with the rules for interactions which precisely rely on the presence of such strings looks to me like a particle physics analog of what J. Heller in his famous novel with the same title calls a "catch 22" situation, a situation which offers no way out; the quantization gives an infinite component pointlike field, but this is not what one needs for implementing interactions in terms of worldsheets. This mismatch explains why in the more than 40 year history of ST it was not possible to find an operational definition of interacting strings. It is not only in the banking sector where people deal with metaphoric bubbles.

5 Genuinely string-localized objects in spacetime and gauge theories

The localization concept of QM referred to as "Born-localization" is based on the Born probability-density associated with x-space Schroedinger wave functions. It is directly related to the spectral decomposition of the Hermitian position operator; in fact the projectors \(E(\mathcal{O})\) measure directly the probability to find the particle (at fixed time) in the spatial region \(\mathcal{O}\). This quantum mechanical localization operator has a multiparticle generalization to (bosonic or fermionic) Fock space, but it is incompatible with Poincaré covariance and causality (propagation in a theory with a maximal velocity); there is no operator
which localizes in spacetime regions in a frame-independent way.

The problem to find a localization which is compatible with special relativity and causality attracted Wigner’s attention already in the early days of QFT; after he discovered the first intrinsic classification of (noninteracting) relativistic particles he hoped to find an autonomous path toward QFT via a relativistic concept of localization. Here "intrinsic" or "autonomous" stands for "properly quantum" i.e. without using any classical parallelism as one does in quantizing a classical Lagrangian field theory. This is an important point because any theory which claims to be more fundamental than its predecessor, should be able to arrive at its main results without referring to a less fundamental theory. To delegate the intrinsic understanding of the localization underlying QFT to the one inherent in classical Lagrangians was not acceptable from Wigner’s foundational viewpoint.

Together with his collaborator Newton, Wigner adjusted the Born localization to the relativistically invariant inner product of relativistic wave functions. In this way the violation of covariance and causality of the "Born-Newton-Wigner" localization becomes manifest.

Of course Wigner knew that QFT comes with a relativistic and causal localization which is inherent to pointlike quantum fields, but quantum fields even within one specified model of QFT are highly nonunique. In fact the existence of an ever increasing zoo of physically equivalent but different looking free field equations during the 30s was his principle motivation for the intrinsic representation theoretical approach over quantization methods which created this zoo.

If one could find a unique covariant and causal localization on the level of one particle states, then the functorial relation between causally localized one particle subspaces and von Neumann subalgebras of the total Weyl (CCR) or Dirac (CAR) algebra would secure (at least for theories without interactions) an intrinsic new localization concept which is by construction independent of which pointlike generating field one uses to describe the spacetime indexed net of local algebras.

The fact that for a given spin there are infinitely many admissible spinorial free fields $\Phi^{(A,B)}$ and each one gives rise to infinitely many Wick-ordered composites would be no problem as long as the causal localization property itself is unique. Despite its impressive observational success, Wigner always maintained a certain distance to QFT. The intrinsic localization concept was only found in the last two decades long after Wigner’s lifetime. In the present context of representation theory it can be found in [37,39], and, in a more special context already in [36] and older publications cited therein.

Wigner’s sceptical view about the imperfections of QFT resulting from a lack of intrinsic understanding of its most central localization properties was well justified because recent progress on existence proofs for a certain nontrivial family of two-dimensional models uses modular localization properties in an
essential way \[25\] and a mathematical control in higher dimensional QFT is hardly conceivable without this new intrinsic localization setting. Only if one is in the possession of sufficiently many nontrivial models about which one has a mathematical control of their existence and properties, one can claim that QFT can be called a theory on par with all the other mature physical theories as mechanics, electrodynamics, statistical mechanics and quantum mechanics. It is one of the main points of this essay to show that modular localization plays a crucial role in this process.

A good understanding of the issue of localization also strengthens the understanding of the content of the previous section; after learning that ST leads to pointlike generated infinite component wave functions rather than to vibrating strings in spacetime, it is interesting to know how genuine string-localized objects really look like.

In view of the fact that even for such eminent physicists as Wigner the issue of localization was fraught with problems and perils, the critique of ST and the string community is obviously not a gleeful reprimand of a committed conceptual error. What is really worrying and distressing is not so much the error itself, but rather the absence of any profound criticism afterwards over several generations. For almost four decades particle theory for a majority of physicists consisted in executing calculational recipes, formal games with functional integrals and occasionally using sophisticated geometry and topology i.e. in activities which are not of much help in conceptual problems related to localization.

This raises the question about the addressee of an article like this. Is it to encourage those who know better but prefer to be silent (section 7), or to loosen up the mind of the hardened string theorists, or is it to strengthen the mind of the uncommitted sceptic? Even if it does not achieve anything of this, it certainly will be helpful for future historians and philosophers because it is part of their professional obligations to say something about what was going on in particle theory in all these years and why even the standard model and more specifically gauge theory went into stagnation shortly after its impressive start.

The localization aspect of ST is the most accessible illustration its misunderstanding caused by its geometrical appearance in the source target relation as compared with its intrinsic physical meaning. There are many other such misleading metaphors obtained from naively identifying geometry with localization. One which is very close to that of ST is the idea that one can embed a lower dimensional QFT into a higher dimensional one. This is not possible, but what one can do is restrict a QFT on a spacetime manifold to a submanifold. However if the submanifold contains the time axis (a "brane"), the restricted theory has too many degrees of freedom in order to merit the name "physical", namely it contains as many as the unrestricted [31]: the naive idea that by using a subspace one only gets a fraction of phase space degrees of freedom is a delusion, this can only happen if the subspace does not contain a timelike line as for a null-surface (holographic projection onto a horizon).

The geometric picture of a string in terms of a multi-component conformal field theory is (section) that of an embedding of an n-component chiral theory into its n-dimensional component space (referred to as a target space), which
is certainly a string. But this is not what modular localization reveals, rather those oscillatory degrees of freedom of the multicomponent chiral current go into an infinite dimensional Hilbert space over one localization point and do not arrange themselves according to the geometric source-target idea. A theory of this kind is of course consistent but ST is certainly a very misleading terminology for this state of affairs. Any attempt to imitate Feynman rules by replacing word lines by word sheets (of strings) may produce prescriptions for cooking up some mathematically interesting functions, but those results can not be brought into the only form which counts in a quantum theory, namely a perturbative approach in terms of operators and states.

ST is by no means the only area in particle theory where geometry and modular localization are at loggerheads. Closely related is the interpretation of the Riemann surfaces, which result from the analytic continuation of chiral theories on the lightray/circle, as the ”living space” in the sense of localization. The mathematical theory of Riemann surfaces does not specify how it should be realized; if its refers to surfaces in an ambient space, a distinguished subgroup of Fuchsian group or any other of the many possible realizations is of no concern for a mathematician. But in the context of chiral models it is important not to confuse the living space of a QFT with its analytic continuation. For the case at hand this means that the chiral model is in a KMS temperature state with respect to the conformal Hamiltonian. The analyticity region is a torus and the boundary values taken on its two cycles are the ”living space” of two chiral theories which, apart from one theory being at the dual temperature of the other, are the same theories i.e. the situation is selfdual. The spacetime interpretation of this situation in the sense of a worldsheet is a totally misleading metaphor. Again we are reminded that localization is a much more holistic notion than geometry. In the case of the torus, one cycle may be that of a the living space of a compactified chiral theory, but the other creates a thermal aspect (a state with vacuum polarization clouds). The simple picture of QM where particles occupy pre-assigned energy levels is never valid in the presence of interactions.

Whereas geometry as a mathematical discipline does not care about how it is concretely realized the geometrical aspects of modular localization in spacetime has a very specific geometric content namely that which can be encoded in subspaces (Reeh-Schlieder spaces) generated by operator subalgebras acting onto the vacuum reference state. In other words the physically relevant spacetime geometry and the symmetry group of the vacuum is contained in the abstract positioning of certain subalgebras in a common Hilbert space and not that which comes with classical theories.

The dominance of the geometric-mathematical point of view over the physical intrinsic localization-based interpretation started at the time of the Wess-Zumino-Witten-Novikov model. Its predecessors, the various prior publications on the multicomponent Thirring models in the setting of current algebras have

\footnote{This is a special case of the Nelson-Symanzik duality for d=1+1 massive theories.}
a seamless relation to modern modular localization whereas the functional W-Z-W-N action representation was invented because in those days there was a prejudice that in order to really understand something, one has to bring it into a geometric-topological form with the help of a functional integral representation. This added a non-intrinsic topological element which may is interesting for mathematicians but did not add anything to QFT; concrete calculations for these soluble models are still done in the representation theoretic setting. In fact no chiral model has ever been constructed under mathematical control with geometric functional integral method.

Another illustration of this point are the recent constructions for factorizing models rely on modular localization [42]; it would be hard to imagine results of a non-metaphoric kind to come from the geometric path integral setting. As most metaphoric tools their main purpose is to facilitate communications between workers with different backgrounds and not model constructions.

Something similar happened with 3-dimensional plektonic models (models with braidgroup statistics). They were geometrically visualized in terms of Chern-Simons actions, and the messages that a euclidean geometric action has to pass a sophisticated Osterwalder-Schrader positivity test before it can be called a QFT was largely ignored. The correct representation theoretical way would consists in the use the 1+2-dimensional Bargman extension of the Wigner representation theory (44 and previous papers of the same author cited therein) which combined with modular localization leads to string-localized algebras on the covering space whose generators fulfill braid group commutation relations. The generators of the wedge algebra are generalized Wigner creation/annihilation operator whose braidgroup commutation relation play a similar role as the operators of the Zamolodchikov-Faddeev algebra in d=1+1.

The modern version of the old representation theoretical methods is the modular localization method which shows its true power in generalizations of Ising like QFTs [43]. By noting that the Zamolodchikov-Faddeev algebra admits an interpretation in terms of modular localization in the region of a wedge [50], the Karowski-Weiss bootstrap-formfactor program was enriched by modular method which are powerful enough to secure for the first time the mathematical existence of interacting nontrivial models with strictly renormalizable short distance behavior [42].

In order to dispel the impression that I am a post-dicting fault-finder who looks gleefully at blind alleys in the past struggle for the correct path in particle theory, I should mention that I enthusiastically embraced the arrival of that perfect blend of geometry, analysis and topology known as the Atiyah-Singer index theory. Suddenly the connection between zero modes of matter fields and winding numbers of gauge configurations which was observed in certain exactly soluble two-dimensional models was understood [45]. After a couple of years my enthusiasm faded when I realized that this quantum mechanical method is limited to Euclidean field theory and there was no easy passage through

\[22\text{This step still needs to be carried out. Since the raison d'etre for modified commutation is the implementation of braid group statistics and not of interactions, the resulting theory which has very nontrivial vacuum polarization is the QFT of a "free" plekton (anyon).}\]
the Osterwalder Schrader positivity requirement in order to find its real time localization counterpart. Ideas around the A-S index theory were popular in the 80s when they were used to classify euclidean gravity models according to their topological anomalies. This direction of research petered out at the end of the 80s.

In QM, where path integral representations had a solid mathematical basis, it was difficult to use them outside of quasiclassical approximations. There was a famous problem at that time posed by L. Schulman, namely to show why the summation over all quasiclassical saddlepoint contributions of the rigid top action (and generalizations beyond SO(3)) leads to the correct result. The analog of this problem in finite dimensions was covered by the Duistermaat-Heckmann theory. I spent almost two years on its infinite-dimensional generalization before giving up. The message I drew from this futile attempt was that if this does not work for geometric problems in QM, there is a fortiori no chance for geometrical QFTs as d=1+1 sigma models to work along those lines. The conclusion was that the best bet for actually constructing models consists in the use of operator methods. In the case of the rigid top the problem has a simple solution in terms of group representations and in d=1+1 the idea of modular localization applied to the family of factorizing models [36] does secure their mathematical existence [42].

The main point of the present criticism, namely the localization problem of ST (section 2) was noticed even by some string theorists, but ”massaged away” under the influence of the TOE ideology and as a result the string metaphor was preserved. In more concrete terms, the commutator of the alleged stringfield associated with the Nambu-Goto Lagrangian was correctly computed and its pointlike field nature was noticed, yet the field was declared to be an ”invisible” spacetime string, apart from one point on the string identified with the c.m. of the invisible string.

In this way the hard-won and proudly cherished conceptual autonomy of quantum theory, which started with profound theoretical considerations and Gedankenexperiments testing the philosophical range of the new QM by Bohr, Heisenberg and others became eroded. Their old message was to abandon any non-observable metaphoric relics from classical thinking, but this has withered away in the modern setting of ST. Even if this theory enters the dustbin of history in the future, the metaphoric fallout of its discourse will linger on for a long time to come. It would be a big loss if ST fades away because it did not lead to observational consequences and not because it is conceptually untenable.

Getting back to the history of localization, the modern causal localization concept called ”modular localization” would probably have pleased Wigner, but unfortunately it only appeared in the late 90s. Its predecessor, the (Tomita-Takesaki) ”modular theory of operator algebras” arose in the middle 60s, the inspiring idea on the physical side came from the formulation of thermal statistical mechanics for open systems [33]. Less than a decade later also the relation between the modular theory and wedge localization was understood [34] which soon afterwards led to a fundamental understanding of the thermal aspects of the Hawking Unruh localization behind black hole horizons. The spatial mod-
ular theory goes back to some unpublished remarks of Longo and entered the work in [30][37][38] and [39]. As mentioned before, together with the modular reformulated bootstrap-formfactor program, it finally led to the first mathematical constructions of strictly renormalizable models (models whose short distance behavior is worse than that of free QFTs).

To give a detailed account of modular localization would go beyond the scope of an essay. In the following we will explain some of the concepts in the context of the simplest particle representation: a scalar massive particle. In this case the Wigner representation of the Poincaré group acts as follows:

$$H_{W_{ig}} = \left\{ \psi(p) \big| \int \psi(p)^* \psi(p) \, d^3p < \infty \right\}$$

$$(u_{W_{ig}}(a, \Lambda)\psi)(p) = e^{ipa} \psi(\Lambda^{-1}p)$$

We now define a subspace which, as we will see later on, consists of wave function localized in a wedge. We take the standard $t-x$ wedge $W_0 = (x > |t|, x,y$ arbitrary) and use the associated Lorentz boost $\Lambda_{x-t}(\chi) = \Lambda_{W_0}($).

$$\Lambda_{W_0}(\chi) : \begin{pmatrix} t \\ z \end{pmatrix} \rightarrow \begin{pmatrix} \cosh \chi & -\sinh \chi \\ -\sinh \chi & \cosh \chi \end{pmatrix} \begin{pmatrix} t \\ z \end{pmatrix}$$

which acts on $H_{W_{ig}}$ as a unitary group of operators $u(\chi) = u(0, \Lambda_{z-t}(\chi))$ and the $x-t$ reflection $j : (x,t) \rightarrow (-x,-t)$ which, since it involves time reflection, is implemented on Wigner wave functions by an anti-unitary operator $u(j)$. One then forms the unbounded$^{23}$ “analytic continuation” in the rapidity $U_{W_{ig}}(\chi \rightarrow -i\pi \chi)$ which represents an unbounded positive operators. Using a notation which harmonizes with that of the modular theory in mathematics [40], we define the following operators in $H_{W_{ig}}$

$$\delta_{it} = U_{W_{ig}}(\chi = -2\pi t) \equiv e^{-2\pi iK}$$

$$\mathfrak{s} = j\delta_{it}^* j = U_{W_{ig}}(j), \; \delta = \delta_{it}|_{t=-i}$$

$$(\mathfrak{s}\psi)(p) = \psi(-p)^*$$

Since the anti-unitary operator $j$ is bounded, the domain of $\mathfrak{s}$ consists of all vectors which are in the domain of $\delta_{it}^*$. With other words the domain is completely determined in terms of Wigner representation theory of the connected part of the Poincaré group.

In order to highlight the relation between the geometry of the Poincaré group and the causal notion of localization, it is helpful to introduce the real subspace of $H_{W_{ig}}$ (the closure refers to closure with real scalar coefficients).

$$\mathfrak{R} = \overline{\{ \psi | \mathfrak{s}\psi = \psi \}}$$

$$doms = \mathfrak{R} + i\mathfrak{R}, \; \mathfrak{R} + i\mathfrak{R} = H_{W_{ig}}, \; \mathfrak{R} \cap i\mathfrak{R} = 0$$

$^{23}$The unboundedness of the $\mathfrak{s}$ involution is of crucial importance in the encoding of geometry into domain properties.
The reader who is not familiar with modular theory should notice that these modular concepts are somewhat unusual and very specific for the important physical concept of causal localization; the fact that despite their physical significance they have not entered the general mathematical physics literature and remain unknown outside a tiny group of theorists underlines the observation that the mainstream of particle physics has favored geometry and neglected quantum localization.

One usually thinks that an unbounded anti-unitary involutive \( s^2 = 1 \) operator which has two real eigenspace associated to the eigenvalues \( \pm 1 \) as something very peculiar, but its ample existence is the essence of causal localization in QFT.

The second line \( (11) \) defines a property of an abstract real subspace which is called standardness and the existence of such a subspace is synonymous with the existence of an abstract \( s \) operator affiliated with that subspace.

The important analytic characterization of modular wedge localization whose mathematical origin is the existence of a dense domain \( \text{dom}_s \) for the unbounded involution \( s \) consists in the strip analyticity of the wave function in the momentum space rapidity \( p = m(c\hbar \chi, p_\perp, s\hbar \chi) \). The requirement that such a wave function must be in the domain of the positive operator \( \delta^+ \) (the operator responsible for the unboundedness) is equivalent to the analyticity of the wave function \( \psi(p_\perp, \chi) \in \text{dom}_s \) in the strip \( 0 < \chi < \pi \) together with the action of \( s \) \( (10) \) which relates the particle wave function on the lower boundary of the strip which is associated to the antiparticle wave function on the negative mass shell. It is easy to see that the dense subspace of such wave functions equipped with the graph norm of \( s \) becomes a Hilbert space in its own right.

This relation of particle to antiparticle wave functions is the conceptual germ from which, after generalization to the interacting setting, most fundamental properties of QFT, such as crossing, existence of antiparticles, TCP theorem, spin-statistics connection and the thermal manifestation of localization originate. Apart from special cases this fully quantum localization concept cannot be reduced to support properties of classical test functions.

More precisely the modular localization structure of the Wigner representation theory “magically” preempts properties of a full QFT on the level of the Wigner representation theory; this follows from the realization that scattering theory permits to extend these one-particle properties to the interacting QFTs \( (11) \). The crossing relation is one these properties resulting from modular localization. This brings this property into a sharp contrast with understanding of crossing behind the Veneziano duality; most of the ideas which came out of the S-matrix setting starting in the 60s was not only observationally without success, but also needs careful critical conceptual attention.

The sharper than wedge localization in causally closed subregions of a wedge (spacelike cones, compact double cones) is obtained by intersecting \( R \) spaces for wedges in different positions \( (37) \). These intersected \( R \) spaces are again related to modular \( s \) operators (with no direct relations to the representation theory of the Poincaré group). Among the 3 families of Wigner representations
(massive, finite spin massless, infinite spin massless) the infinite spin family has trivial compact localization subspaces with the tightest localized nontrivial subspaces being semiinfinite string-like localized (the singular limit of spacelike cones). Such quantum matter cannot be generated by pointlike fields. The case of zero mass finite helicity is also quite interesting since certain covariant potentials, unlike in the massive case, do not exist as pointlike but rather only as semiinfinite stringlike objects. We will return to this observation in more detail below.

From the spatial modular localization setting of Wigner’s representation theory one can directly pass to the of interaction-free net of local algebras by exploiting the functorial relation between real subspaces and von Neumann subalgebras [37][39]. On can also use the Wigner representation data to construct the covariant fields. According to the previous section one only needs to determine the $u(A\dot{B},s)\cdot(s; p, s_3)$ intertwiners and their conjugates. This can be either done by group theory (covariance) as in Weinberg [19] or by using modular localization. The second method also works in the case of string-like localization.

It is helpful to rewrite the above result about the oscillator-driven infinite dimensional representation of the Poincaré group into the more conventional setting of irreducible free fields.

For this purpose it is helpful to recall the form of the most general covariant free field of mass $m > 0$ and spin $s$

$$\Psi^{(A\dot{B},s)}(x, m) = \frac{1}{(2\pi)^{3/2}} \int (e^{-ipx} \sum_{s_3=-s}^{s} u^{(A\dot{B},s)}(s; p, s_3)a(s; p; s_3) + h.c.) \frac{d^3p}{2\sqrt{p^2 + m^2}}$$

$$\left[\Psi^{(A\dot{B},s)}(x), \Psi^{(A\dot{B},s)\ast}(y)\right]_{grad} = i\Delta^{(A\dot{B},s)}(x - y; m)$$  \hspace{1cm} (12)

The meaning of the notation is as follows. The $A, \dot{B}$ are the Casimir values which characterize the irreducible $(2A + 1)$ component undotted respectively the $(2\dot{B} + 1)$ component dotted spinor representations. For a given physical spin $s$ there is an infinite supply of covariant fields. They are described by admissible triples $(A, \dot{B}; s)$ which are characterized by the inequality $|A - \dot{B}| \leq s \leq A + \dot{B}$.

For a given such triple there is precisely one $(2A + 1)(2\dot{B} + 1)$ dimensional irreducible representation of the two-fold covering $\widetilde{O}(1, 3)$ of the Lorentz group but for a fixed $s$ there is a denumerable infinity of spinorial descriptions i.e. free fields which all belong to the same Wigner representation and therefore share the same Wigner creation (annihilation) operators $a^\ast(s; p; s_3)$; their only difference is in the $u^{(A\dot{B},s)}$ system of intertwiners and their conjugates (the $v$-intertwiners) [19]. The $(2A + 1)(2\dot{B} + 1)$ column indices of the intertwiners have been suppressed. Needless to add that these objects are explicitly known. They define the pointlike covariant wave functions. The (graded) commutator of two covariant fields is a covariant polynomial in spacetime derivatives acting on the spinless $\Delta(x - y)$ commutator function. All these objects have been computed in the literature [35][20] in terms of known functions.
Besides the massive family there are two irreducible massless representation namely the zero mass finite helicity representation \((m = 0, s)\) and the zero mass "infinite spin" representations \((m = 0, \kappa)\) whose spin analog is a continuous Casimir parameter \(\kappa\). The infinite dimensional unitary representation of (the covering of the) Poincaré group, leading to the infinite dimensional wave function of ST in the previous section, does not contain this third kind of massless representation and hence is point-localized and leads to pointlike free fields.

The covariant form of the zero mass finite helicity representations lead also to a undotted/dotted spinorial calculus as above, however there is a small but important distinction; instead of the full range of admissible \((A, \dot{B})\) values one is only left with spinorial representations with \(|A - \dot{B}| = s\), i.e. the physical spin equals the absolute value of the difference between the dimension of the undotted and dotted "Lorentz spins". This considerably reduces the possibilities, but there remains still an infinity of covariant fields for a fixed \(s\). In the case \(s = 1\) the field strength tensor is associated with \((m=0, s=1)\) is an allowed covariant pointlike field, but there is no pointlike covariant vectorpotential consistent with the unitary representation theory of the Poincaré group. It turns out that covariant vectorpotentials do exist if one lifts the pointlike restriction in favor of semiinfinite stringlike localization. In fact the full range of admissible possibilities of the massive case can be restored in the massless family if one permits string localized fields\(^{24}\). It turns out that for \((m = 0, s \geq 1)\) the covariant fields with the lowest short distance dimension are always semiinfinite string-localized.

In the interacting case there is no such functorial relation, however in this case the validity of the modular theory for wedges (the Bisognano-Wichmann property) can be related to free case by invoking scattering theory\(^{11}\). The fact that the noncompact wedge algebra still permits affiliated operators which applied to the vacuum create vacuum-polarization-free (PFG) states is of crucial importance in recent existence proofs for factorizing models\(^{36\,38}\).

Modular localization theory reveals that, contrary to the quantum mechanical Born-Newton-Wigner localization which is related to position operators and a family of space-dependent projectors \(E(O)\), the localization subspace in the Hilbert space \(H\) of a QFT is defined as the dense domain of the algebraic modular (Tomita) involution \(S\) associated with a "standard" pair \((\mathcal{A}(O), \Omega)\) where \(S\) is defined as
\[
SA\Omega = A^*\Omega, \quad A \in \mathcal{A}(O)
\]
\[
H(O) \equiv \text{dom}S = K(O) + iK(O), \quad \overline{H(O)} = H
\]

Here the real subspaces \(K(O)\), \(iK(O)\) are the \(\pm\) eigenspaces of the Tomita \(S\)-operator. For an interaction-free theory the \(K(O)\) and their complexification are Fock space generalizations of the subspaces\(^{11}\) of the Wigner representation.

\(^{24}\)Modular localization never leads to finite strings as in ST, semiinfinite spacelike strings appear because they are the core of the simplest noncompact simply connected causally complete regions (spacelike cones) as points are the core of the simplest compact simply connected causally complete. This has nothing in common with closed or open wiggling strings of ST.
space. It is not our intention to explain the details of modular theory, the only point to which we want to direct the attention of the reader is that, contrary to the B-N-W localization, which leads to bona fide subspaces and projectors, the information of causal relativistic localization is encoded in dense subspaces $H(O)$ (or equivalently in the real subspace $K(O)$) which change continuously with the spacetime region $O$ and are determined in terms of the representation of the Poincaré group i.e. all models with the same particle content have the same spacetime indexed net of dense subspaces $H(O)$. The Tomita $S$-operator contains more detailed information about the interaction. For the case of the wedge region $O = W$ the polar decomposition of $S$ contains the $S_{\text{scat}}$-matrix

$$S = J \Delta^\dagger, \quad J = J_{\text{in}} S_{\text{scat}}$$

Here $\Delta^\dagger$ is (up to a rescaling) the unitary representation of the W-preserving boost group. $J$ is the anti-unitary modular reflection operator which transforms the algebra $A(W)$ into its commutant $A(W)' = A(W''^{25})$. $J$ can be decomposed into the anti-unitary reflection operator of the incoming interaction-free situation $J_{\text{in}}$ and the unitary scattering matrix $S_{\text{scat}}$. Hence modular theory does not only define the intrinsic content of causal localization but it also attributes a hitherto unknown role to the scattering matrix: $S_{\text{scat}}$ is a relative modular invariant between the interacting and the free wedge algebra; with other words $S_{\text{scat}}$ is not only that global object which connects with QFT through the asymptotic LSZ limit but it is also in a very deep way related to the semi-local wedge algebra. In fact the recent existence proofs for factorizing models, which are the first existence proofs for strictly renormalizable models in the history of QFT, depend precisely on this modular. Such concepts and mathematical objects one does not meet anywhere in QM. These contrasts can be traced back to the local algebras: whereas local algebras in QM are always of the same type as the global algebra namely type I factors, the local algebras of QFT are all equivalent to the unique hyperfinite type $\text{III}_1$ factor (the monad). This leads to the extraordinary result that the full content of a QFT can be encoded into the positioning of a finite number of copies of the monad into one Hilbert space, a potentially powerful new structural property of QFT whose exploration is only beginning.

But the fact that the B-N-W localization violates covariance and causality does not mean that it is of no use in QFT. For asymptotically large timelike separation of B-N-W localization events the relation becomes causal and covariant and this asymptotic covariance is sufficient to prove the Poincaré invariance of the $S$-matrix; last and not least the cross section$^{26}$ is a probability and it would be a disaster for relativistic QFT if B-N-W would not be at least asymptotically invariant ("effectively" outside a Compton wave length).

---

25The equality between the commutant and the geometric opposite algebra follows from the proof of the Bisognano-Wichmann theorem 11.

26In fact Born in his famous paper did not link the probability interpretation of QM with the absolute square of the Schroedinger wave function but rather with the cross section as it arose in the Born approximation.
For the rest of this section we will return to the matter of our principle concern: string-like localization.

In a theory which is generated by pointlike fields it is always possible to introduce string-like localized generators. There are two cogent reasons for doing this. One is that for each pointlike covariant free field $\Psi(x)$ one can construct an associated semiinfinite string-like localized spinorial fields $\Psi(x,\epsilon)$ with

$$U(a,\Lambda)\Psi(x,\epsilon)U^*(a,\Lambda) = D(\Lambda^{-1})\Psi(\Lambda x + a,\Lambda \epsilon)$$

$$[\Psi(x,\epsilon),\Psi(x',\epsilon')]_{\text{grad}} = 0, \quad x + \mathbb{R}_+ \epsilon > < x' + \mathbb{R}_+ \epsilon'$$

The first line expresses the covariant covariant transformation property of the string-like free field which lives in the same Wigner-Fock space as the pointlike field. The second line justifies the name "string-like localized" since the graded commutator only vanishes if all points of the two linear strings which start at $x$ and $x'$ are spacelike relative to all points on the second string. In this way the string become visible if one enters the causal dependenc region of the other; this kind of causal visibility is part of the definition.

The first cogent reason for passing from $\Psi(x)$ to $\Psi(x,\epsilon)$ is that the string-localized counterparts have better short distance properties: instead of the well-known increase of the short distance dimension (sdd) with spin $s$, the string localized $\Psi(x,\epsilon)$ can be chosen such that

$$\text{sdd}\Psi(x,\epsilon) = 1 \quad \forall \quad s$$

which is the formal power counting prerequisite for renormalizability up to quadrilinear interaction terms. Renormalizability is however more than power counting. The standard approach uses properties of relative pointlike localization in an essential way; this is borne out in the formulation of Epstein and Glaser where the parametrization of the freedom in passing to the next perturbative order depends on the pointlike localization in an essential way. Hence one needs a very nontrivial adjustment to the new string localization; this is presently being investigated. A E-G approach to string like fields would certainly enlarge the range of renormalizable models; whereas before the renormalizability stopped at $s=1$, the power-counting requirement for renormalization is valid for all $s$.

Another cogent reason arises in connection with zero mass finite helicity representations. In that case, as was briefly mentioned in the previous section, the admissible covariant fields are severely restricted, namely instead of the inequality between the formal spins $A, B$ and $s$ one has the more restrictive equality $s = |A - B|$ \[13\]. This restriction prohibits pointlike covariant vector-potential for photons and gluons and metric $g_{\mu\nu}$ tensors for $s=2$ (gravitons) and more general pointlike objects for all $(m = 0, s \geq 1)$ representations. The full range of possibilities of spinorial descriptions is however restored if one allows seminfinite string localization.

Among the string-localized fields with sdd=1 there are in particular the $s=1$ vectorpotential $A_\mu(x,\epsilon)$, and the $s=2$ tensorpotential $g_{\mu\nu}(x,\epsilon)$ which are linearly
related to the pointlike field strength and respectively linearized Riemann tensor. For the purpose of a compact terminology let us call the massless pointlike localized fields with $s = |A - \dot{B}|$ "field strengths" and the remaining string-localized spinorial fields which saturate the inequalities (12) "potentials". So free potentials are always string-localized and by appropriately differentiating potentials one obtains pointlike free field strengths.

Already in the absence of interactions the observable algebra generated by the field strength has a subtle structural property which distinguishes it from the corresponding free massive algebras and clearly points towards string-localized objects. In the massive case the algebras fulfill the unrestricted Haag duality namely the property that the local fields which commute with the fields inside a causally complete region are precisely those fields and their composites which are localized in the causal complement

$$A(O)' = A(O)$$

With the exception of regions $O$ which consist of disconnected parts, this Haag duality relation holds for all massive theories even, if $O$ is multiply connected. However for $(m = 0, s \geq 1)$ this is only true for simply connected regions\(^{27}\) for spacetime regions with multiple connectivity (e.g. a toroidal spacetime region) Haag duality is violated

$$A(O) \subsetneq A(O)'$$

$$\mathcal{R}(O) \subsetneq \mathcal{R}(O)'$$

where the second line contains the spatial modular version of the Haag duality violation in which the upper dash on the real subspace $\mathcal{R}$ stands for the symplectic complement within the Wigner space.

In this case there are additional operators which, although they commute with all field strength in the causal complement, and are therefore expected to be objects localized in $O$, cannot be generated by field strength localized in $O$. The explicit calculation was done in a famous (but unfortunately unpublished) paper by Leyland, Roberts and Testard\(^{46}\) for a free Maxwell field strength i.e. $s=1$. For $O$ the authors chose spacelike separated tori $T_i$, $i=1,2$ and construct electric and magnetic fluxes through orthogonal disks $D_i$ whose circular boundaries are the cores of the $T_i$ whose which are interpenetrating in such a way that the spacelike separation is respected. The crucial point is to show that the fluxes through $D_i$ can be chosen in such a way that their electric and magnetic wave function fulfill

$$e_i, h_i \in \mathcal{R}(T_i)'$$

$$Im(e_1, h_2) \neq 0 \neq Im(e_2, h_1)$$

\(^{27}\)For Fermions there is a formulation in terms of graded commutators.

\(^{28}\)The violation of Haag duality for spacelike separated disconnected spacetime regions is related to the existence of charge transporters and leads to the theory of locally generated superselection rules and the concept of inner symmetries.
If there would exist a pointlike vectorpotential \( A_\mu(x) \) then the imaginary part would vanish and there could be no violation of Haag duality. This argument is perhaps the strongest argument against the indiscriminate use of pointlike vectorpotential which lives necessarily in an indefinite space in which localization has no physical significance. A stringlike vectorpotential avoids this contradiction [39], causal completion of a torus obtained by regularizing the boundary of a disk a circle. The above result does not contradict the Stokes theorem but only the classical geometric idea that the magnetic potential on the boundary is localized there. The absence of a pointlike magnetic vectorpotential has no classical counterpart since it is a result of the subtle clash between pointlike localization of a vectorpotential and the principles of quantum theory; the use of the stringlike potential shows that there is a consistent operational derivation of the above result in terms of vectorpotentials.

A classical counterpart (classical only with respect to the electromagnetic field) of this phenomenon is the Aharonov-Bohm effect to be more precise we will consider the violation of Haag duality as the quantum Aharonov-Bohm effect [5]). As in most cases of passing from the classical to the quantum realm, the quantum relation is more subtle than its classical counterpart. There can be no doubt that for \( s > 1 \) there will be extended A-B effects. Since the distance between the dimension of the best (in the short distance sense) field strength and the \( sdd=1 \) of the best potential increases with \( s \) there arises the curious question whether the increase of the possible potentials with \( s \) could lead to an increased violation of Haag duality via fluxes through higher genus tori.

The potentially most promising application of these ideas is to find a substitute or rather an extension of the method of gauge theory. The gauge theory approach uses pointlike potentials and overcomes the representation theoretical No-Go theorem against the existence of covariant pointlike vectorpotentials through sacrificing the rules of quantum theory by allowing an indefinite metric state spaces in intermediate perturbative computational steps. This problem of positivity and unitarity is absent in the classical gauge theory of electrodynamics and hence despite all formal similarities the conceptual meaning of the word "gauge" differs considerably. In the quantum setting it leads to the introduction of auxiliary ghost degrees of freedom, but apart from this more violation of the rules of quantum theory and the necessity to relate gauge invariance with the necessarily more subtle return (or creation) of a Hilbert space setting, the quantum version of the gauge theory formalism follows its classical counterpart. However this is only true for the local observables; the description of necessarily nonlocal quantum electric charges is outside the gauge formalism. Their nonlocality is the result of a subtle quantum phenomenon which has no counterpart in the classical setting.

In fact the sharpest localization which is possible for electrically charged particles is the semiinfinite stringlike localization, there are no compactly localized charge carrying operators. Since the time of Jordan, Dirac and Mandelstam the simplest formal string representation of a charged field has the form

\[ A_\mu(x) = \int \frac{d^2 \sigma}{(2\pi)^2} \mathcal{F}(\sigma) \gamma_\mu \epsilon(\sigma) \]

In the Coulomb and other representation the em flux is not forced through an infinitely
\[
\Psi(x, e) = \psi(x)e^{\int_0^{\infty} ie\cdot A^\mu(x+\lambda e)d\lambda^\mu}
\]

\[
\Psi(x, e) \xrightarrow{\alpha(\Lambda, a)} D(\Lambda^{-1})\Psi(\Lambda(x + a), \Lambda e)
\]

where the second line is the automorphic action of the Poincaré group. It is prohibitively difficult to lift the quotation marks i.e. to give a precise meaning to this formula within the setting of renormalized perturbation theory. Whereas the unphysical fields \(\psi(x)\) and \(A^\mu(x)\) (which only have a "ghostly" existence) are part of the perturbative gauge formalism, physical charged fields defined in terms of nonpolynomial functions in the unphysical fields as \[17\] are outside this formalism and have to be defined in terms of a special and hardly manageable new formalism \[17\]. One may say that gauge invariance requires charged fields to have noncompact stringlike localization as in \[17\] but this is not very revealing since localization is the raison d’être of QFT whereas gauge invariance is a technical tool which allows to treat massless \(s=1\) interactions with the same renormalization formalism as that used for pointlike \(s=0,1/2\) fields. The prize to pay is precisely that important string-localized fields are outside this formalism and one is confronted with the aforementioned problems. Knowing that gauge theory maintains the known formalism at the expense of the most important principle of QFT, the better strategy seems to be to confront the stringlike localization right from the beginning without any technical crutch which permits the standard setting of renormalizable perturbation theory and to look for a new perturbative renormalization theory which incorporates stringlike localized potentials. The incorrect handling of the localization issue and the transgression of quantum theory by indefinite metric spaces are two sides of the same coin; correcting the first automatically resolves the second \[5\].

The observation by Bloch and Nordsieck \[48\] that the scattering of electrons in QED leads to more radical changes from standard scattering theory in the infrared regime than the quantum mechanical Coulomb scattering was made at the same time as \[17\], but the question whether there is a relation between the momentum space treatment of the emission of infinitely many infrared photon in a collision of charged particles, and the possibly semiinfinite stringlike localization of their charge-carrying fields was not asked.

Only in the 60s the first model studies on this problem begun. It was shown that two-dimensional Lagrangian couplings between massless mesons and massive fermions lead to solutions of the form \[49\]

\[
\psi(x) = \psi_0(x)e^{ig\int_y^x j(y)dy}
\]

where \(\psi_0\) is a massive free Fermi-field and \(j\) a chiral current of a massless Fermi-field. This leads to a analytic momentum space behavior similar to the one observed in \[48\] \[50\] so the notion of "infraparticle" i.e. a particle-like entity which is inexorably tied to its infrared photon cloud and string-localized charged fields appeared as two manifestations of the same phenomenon.
Since in $d=1+3$ QED there is presently no mathematical control on the level of operators, in particular on string-localized charged operator, one must rely on structural arguments which disprove the possibility that there can be compactly localizable generators of charged fields and in this way confirm string-localization as the sharpest possible one. Such a rigorous structural argument follows from a quantum adaptation of Gauss law which also leads to two additional interrelated results namely that the Lorentzgroup on charged states is spontaneously broken and that the velocity direction of the outgoing/incoming particles define superselection rules [1].

But these structural results unfortunately did not lead to a modified perturbation theory for electrically charged fields. The actual computations are still made in the same gauge theory setting as that used more than half a century ago: a formally pointlike vectorpotential in an indefinite metric space and a gauge invariant physical space of local observables which does not contain the string-localized electrically charged objects. The gauge invariant observables correspond in the new setting based on interactions of matter with string-localized vectorpotentials are those which are independent of $e$; since the $e$-dependence only enters through $A_\mu(x,e)$ the criterion for pointlike localization is invariance under the change

$$A_\mu(x,e) \rightarrow A_\mu(x,e') = A_\mu(x,e) + \partial_\mu \Phi(x,e,e')$$

as expected from the gauge theoretic setting, all correlation functions involving products of chargeless operators are independent of $e$ i.e. they are point-instead of string-localized.

In fact the string-localized potential $A_\mu(x,e)$ looks, apart from the fact that a gauge parameter does not change under Lorentz transformations, precisely like the axial gauge potential in that it obeys identical relations $e^\mu A_\mu = 0 = \partial^\mu A_\mu$. The difference is mainly one of interpretation: $e$ is not a gauge parameter but as $x$, a spacetime coordinate (a point in a 3-dim. de Sitter space) in which the field fluctuates. Although $sddx = 1$ it has reached this lowest possible dimension only by deflecting part of the fluctuations into directional fluctuations which are then perceived as infrared divergences. In fact the axial gauge was never used for higher order calculations because in order to deal with these infrared singularities one first has to understand the distributional nature of stringlike fields in $e$ in order to appreciate how to deal with coalescing $e'$s and this was not possible as long as they were considered as gauge fixing parameters.

So the string theoretic alternative to the gauge theory setting should be clear by now; one wants to trade the pointlike indefinite metric potential together with its unphysical Gupta-Bleuler or BRST formalism with a coupling of conserved matter currents to a string-localized vectorpotential $A_\mu(x,e)$ in a Hilbert space. Besides reproducing the gauge invariant subalgebra as the $e$-independent algebra of local observables, the main aim is to understand the

30The $e$-dependence of external lines in Feynman graphs for time-ordered correlations is harmless since it can be removed by passing to field strength which does not change the physical content.
nonremovable stringlike localization of charged fields as resulting from the interactions with stringlike potentials. Whereas the stringlike nature of the latter has no bearing on the charge neutral subspace of the physical Hilbert space\footnote{The cyclic application of $A_{\mu}(x,e)$ and that of $F_{\mu\nu}(x)$ generates the same Hilbert space.}, the more severe\footnote{In distinction to the potentials there is no linear process which removes the strings, only by passing to charge neutral composites this can be achieved.} stringlike nature of charge generators in the perturbative conceptualization results from the interaction with the stringlike vectorpotentials. In setting up a renormalization theory in which stringlike potentials participate there, are 3 points to be observed.

- The power-counting requirement on the interaction polynomial $sdd\mathcal{L}_{int} \leq 4$ otherwise the number of undetermined renormalization parameters will be infinite. But since for arbitrary spin $s$ there is always a string-localized covariant potentials with $sdd\Psi = 1$, there are infinitely many couplings which fulfill the power-counting requirement and thus are potential candidates for representing renormalizable QFTs.

- The iterative $n^{th}$ order step $n \to n + 1$ must be such that the resulting ambiguities are not worse than string localized (the string adapted Epstein-Glaser requirement).

- There must be pointlike local equivalence subclasses of fields i.e. fields whose correlations functions are independent of $e$. In the simplest case of QED this is achieved by the independence of their correlation functions under change of $e$-direction. In case of QED this means that the correlation functions of charge neutral fields must be independent under a change of $e$ which amounts to the substitution \footnote{The Seiberg-Witten view of gauge theory which led to invariants bearing the same name as well as duality structures in gauge theories are (semi)classical observations i.e. their local quantum physical content is not known. The same holds for similar result about results about euclidean gravity invariants.}.

At this point also the weakness of the geometric/topological point of view, which rose to prominence in particular with gauge theory, becomes exposed. It offers answers to questions about fibre bundles and related mathematical subjects\footnote{The Seiberg-Witten view of gauge theory which led to invariants bearing the same name as well as duality structures in gauge theories are (semi)classical observations i.e. their local quantum physical content is not known. The same holds for similar result about results about euclidean gravity invariants.} but does not shed light on quantum physical questions in which localization plays an important role. Since fibre bundles and other classical constructs associated with the Lagrangian formalism contain no reliable information about quantum localization since modular localization has representation theoretic and algebraic origins, the string-localization of charged fields remained outside the Lagrangian perturbative formalism.

The lowest order perturbative expression for the two-point function of the charged field can be computed in terms of the product of the free massive Dirac two-point function with that of the $e$-dependent vectorpotential. As expected, the result cannot return to pointlike localization by any linear operation \cite{5}.
The point 2 in the above list is presently under intense investigation, the
generalization of the E-G iteration to strings is a very nontrivial problem. Higher
orders are expected to strengthen\(^3\) the string dependence.

In this setting of viewing localization as the central concept of QFT, the
Schwinger-Higgs screening of scalar QED is a process of "re-localization" from
the noncompact Maxwell charge to the pointlike "screened charge" i.e. the
Higgs matter and the pointlike massive $s=1$ vectormeson. Figuratively speaking
half of the degrees of freedom of the "pre-screened" charged field has hooked
onto the massless vectorpotential and converted it into a massive vectormeson.
In this way of looking at the problem it becomes the QFT counterpart of the
Debye screening mode of a quantum mechanical Coulomb gas. Locality in the
context of QM becomes the "range of forces"; the concept of modular localization
needs vacuum polarization which is absent in QM. Quantum field theoretic
analogas tend to be more abstract and more radical; the intrinsic meaning of S-H
screening is that there exists a self coupling of real scalar fields and a coupling
with massive vectormesons which leads to a theory which is pointlike generated.
The use of a stringlike massive vectormeson in the coupling to the scalar
field would then only play the role of a "renormalization catalyzer" for main-
taining the power counting restriction. Although the massive vectorpotential is
string-localized, its associated field strength and the screened real scalar field is
pointlike, in other words the model is pointlike generated.

Since Schwinger’s role in this birth of this concept seemed to have been lost
in the maelstrom of time, here are some helpful remarks. Schwinger thought at
the beginning of the 70s that there could exist a screened mode of actual (spinor)
QED in which the photon changes to a massive vectormeson. When he realized
that 4-dimensional spinor QED was not suitable in order to demonstrate his
point, he proposed the 2-dimensional Schwinger model which exists only in this
massive screened mode. About the same time Higgs succeeded in showing that
4-dimensional scalar QED possesses such a perturbatively accessible mode. If
in addition one couples other spinor fields in addition to the Higgs (= screened
complex) field, their global charge will be unaffected, only the Maxwell-charge
of the former complex scalar field will be screened and in this way become a
real field $R$.

Charge screening means that the selection rule of the Maxwell charge breaks
down because

$$^\sim \int j_0(x)d^3x = 0$$

(20)

Here the quotation mark indicates that the definition of charges from conserved
currents requires some mathematical care. The interaction with the real part
contains also a $R^3$ term \(^5\) so that even-odd selection rule is also broken. Al-
though most calculations about Schwinger-Higgs screening are perturbative, the
charge/screening issue is also the subject of a theorem. Swieca’s screening the-
orem \(^5\) in which the occurrence of a massive "photon" (i.e. a massive object
which complies with the Maxwell structure of the interaction) is linked to an

\(^3\)For stringlike fields allow to speak about the strength of their stringlike localization.
increase of analyticity of certain formfactors which indicates an better localization.

Whereas the nonabelian generalization of the screening mechanism has a similarity with its abelian counterpart in that the physical content is that of a system of massive vectormesons and hadrons without having to invoke infra-particles and string-localized interpolating fields, the "unscreened" Yang-Mills theory and QCD remained a mystery. As with any mystery it is the source of folklore and metaphors. This is reflected even in the terminology (gluon, quark) confinement which refers to QM, whereby the use of appropriate potentials can create a vault for particles. However this is not possible in QFT where the only principle is locality; theories with pointlike generators (or compactly localized algebras) can not justify this terminology. The very strong infrared divergencies (stronger than in the abelian case) of correlation functions point into the opposite direction: noncompact localization.

In this context it is interesting to take a closer look at the third class of positive energy Wigner representations, the infinite spin representations. They are string-localized but in a very different way from string-local potentials of zero mass pointlocal field strength and also from states created by a charge-carrying field. Whereas in those cases the state on which the Poincaré group acts contains (under reduction into irreducible components) only pointlike representations, this is remarkably different for the infinite spin representation.

Even if one could generate such a positive energy state by applying interacting finite spin fields (e.g. gluon fields) to the vacuum, it would be impossible to perceive its presence by performing measurements on it. A measurement apparatus in local quantum physics is represented by an operator from a compactly localized subalgebra, but in view of the inexorable vacuum polarization from localization with sharp boundaries it is customary to relax the restriction from local to quasilocal [1]. Such an apparatus can only interact with a finite part of the infinite extended string. The latter should then experience a local change, which is prevented by the irreducibility of the string representation. Similar arguments would lead to the statement that it is impossible to create such strings in collision processes (which is consistent with the string-breaking mechanism).

In earlier times, when the attempts show that a pointlike covariantization of the infinite spin representations failed, these representation were dismissed as "not used by nature" [19]. But knowing that these representation describes irreducible string states and its field theoretic generalization a new kind of string-localized free field theory (which most probably does not even possess pointlike composite fields [39]), and being aware of the need to accommodate the degree of freedom of interacting in the gluons as fields and states but in contradistinction to their abelian relatives the photons not as particles, one should perhaps not outright dismiss this very large third Wigner representation class. It is hard to find a theoretical reason why a representation class which fulfills the energy positivity should be discarded for conceptual reasons in times where the string-localized interacting gluons ask for a better understanding.

This infinite spin representation and its generating field is by itself not very interesting. But if one could find an argument that the interacting string-
localized gluon field applied to the vacuum contains such a string representation
the interest would certainly increase. Unfortunately the wisdom in perturbation
theory seems to be that only those representations which entered in the form
of free fields can be found in the decomposition of interacting states, but this
argument may be to naive. It is also possible that the physics of strong interac-
tions is described by a form of QCD in which the infinite spin representations
enter in some other form. But in no way can invisibility in QFT result from
confinement into a vault.

Some hint about the severity of the infrared divergences caused by gluon
string fields should be contained in the infrared divergencies in the string direc-
tion $e$ which are much stronger in the Yang-Mills case than in correlation func-
tions of charged fields in QED. Whereas the standard gauge theory approach
has no means to avoid these divergences, the string setting treats the string
directions $e$ on the same level as the $x$ i.e. one needs a testfunction smearing.
In this setting the calculation of coalescing $x$'s is expected to be similar to the
calculation of composite fields. Whatever the progress on Yang-Mills and QCD
will lead to, the stringlike localization will remain the important issue. The rea-
son why this issue appears in an essay with the title "ST deconstructed" is that
ST has succeeded to create a tremendous amount of confusion and derailment
in a area which is central to particle physics and which has to be regained in
order to end the almost 4 decades lasting stagnation on the crucial project of
the standard model.

Even though this perturbative realization of the Schwinger-Higgs screening
picture works, it is always advantageous to ask whether a certain way of doing
things is still afflicted with residues of metaphors even if, as in this case, the
metaphors have been helpful. Since the observable massive vectormeson does
not reveal in any observational manner whether it is coming from a (fattened)
photon or not, an anti-metaphor cleansing is physically justified. Indeed, by
using the BRST formalism in a perturbation setting, starting with massive
vectormesons, one derives that, in order for the BRST formalism to lead to
the expected cohomological properties, one needs to introduce an additional
physical degree of freedom whose simplest realization is an interacting massive
scalar field (naturally without a vacuum "condensate") \cite{54,55} of the same kind
as the real scalar field after the Schwinger-Higgs screening mechanism has done
its job. This looks as one has finally succeeded to show that the presence of a
renormalizable vectormeson requires to be accompanied by a $s=0$ particle.
If it would not be for the BRST indefinite metric aspect, this would be the
end. But one cannot base a general statement like this on arguments using
indefinite metric or to put it in more drastic terms: one cannot extinguish
fire with gasoline. Hence the last step would consist of starting with massive
string-localized (and therefore "power-counting renormalizable") vectormesons
and find out whether the requirement that the perturbation theory is pointlike
generated (or at least admits pointlike subobservables) requires the presence of a
scalar "companion". The presence of lower spin objects as a result of the locality
requirement would be the "ultimate" step in the understanding of the Schwinger-
Higgs mechanism within a theory in which all properties are realizations of
the locality principle under different circumstances; it would certainly be much
deeper than the rather dull appearance of families of particles with different
spins as a result of supersymmetry.

The merger of gauge theory into the setting of string-localized fields is quite
satisfactory because the analogy to the classical gauge theory which finds its
mathematical setting in fibre bundles is not helpful; there is no classical ana-
log of unitarity and Hilbert space structure since a classical vectorpotential is
like any other pointlike classical field. The modular localization is an intrinsic
quantum attribute and any property one encounters in QFT must be resolved
in terms of localization properties, only then one can claim to have under-
stood its roots. This does not only apply to string-localization of generators
of electrically charged algebras and their pointlike "re-localization" in terms of
Schwinger-Higgs screening and the still poorly understood invisible nature of
gluons in Yang-Mills theories, but includes also such well-understood issues as
the existence of superselection sectors and the associated internal symmetries.

Although QFT is very indigent about principles, it is quite abundant and in-
genious in the different realizations of its only principle: causal localization. As
the above illustrations show, it takes some skill to show that a certain property
in QFT is a manifestation of locality. Therefore the incorrect understanding of
the crossing property and the misleading belief that duality is its one-particle
approximation, as well as the later misunderstanding in interpreting multicom-
ponent chiral models as defining an embedding of a string into the target (=
component) space, each one of these conceptual errors is in the realm of hu-
man weakness confronting the most subtle physical principle on which already
Wigner despaired. After all QM in distinction to QFT has no intrinsic notion
of localization; where a quantum mechanical string is "localized" in spacetime
or in an internal Hilbert space is specified by the person who carries out the
computation. Not so in QFT which thanks to its intrinsic modular localization
can very well distinguish between a string in spacetime and a collection of oscil-
lators in a "little Hilbert space" which are able to change the relative admixture
in an infinite particle/spin tower "above" spacetime.

In this way the superstring is what we called a dynamical infinite component
pointlike field, the first and only successful construction of an earlier research
program which was restricted to group theory (noncompact groups which gen-
eralize the Lorentz group [20]) and ended in failure. So the misunderstandings

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\textsuperscript{35} All the local algebras in QFT are of the same type and are for brevity referred to as a

markdown

monad.
of the delicate causal relativistic localization is not different from other conceptual misconceptions in the history of theoretical physics. But never before had a misconceived idea that much success that it remained in the headlines of physics journals for 5 decades and recently even led to a new string-oriented IOP journal. From a scientific point of view it is nearly impossible to understand how such an incorrect idea, which in 50 years was not able arrive at any observationally verifiable prediction (but "postdicted" General Relativity, as their followers claim), but led to thousands, if not ten-thousands of publications and is still supported by what are considered the to be leading particle physicists [53]. To shed some light into what has been going on will be a herculean task for historians and philosophers of science, and it is my hope that essays like this may give some guidance in this conceptual slippery terrain.

6 Quantum Kaluza-Klein reduction and the degrees of freedom problem

The Kaluza-Klein proposal originated in the aftermath of Einstein`s general relativity as an attempt to obtain a geometric unification with the classical Maxwell theory by passing to a 5-dimensional Einstein-Hilbert theory and imposing an appropriate restriction on the 5\textsuperscript{th} spatial dimension. The restriction consisted in assuming that the coordinate is compact i.e. circular and that in its Fourier transform only the lowest frequency enters ("dimensional reduction" via a shrinking circle).

As we learned in the previous section a geometrical unification may be compatible with a classical setting, but there is a priori no reason to believe that it fits into QFT with its modular localization. Even on a classical level there arises the question what is really gained if the reduction of 5 dimensional Einstein-Hilbert gravity by a special prescription for the compactification of one spatial dimension leads to the 4-dimensional coupled Einstein Maxwell system which of course one also could have obtained directly by adding to the energy-stress tensor the Maxwell contribution. The fact that the Kaluza-Klein (K-K) idea did not play any significant role in classical general relativity could be interpreted as indicating that it does not go beyond a nice metaphor which does not enrich or simplify any calculation nor is there any conceptual gain.

The local quantum physical setting is completely intrinsic in the sense that all physically meaningful properties do not depend on how the model was produced (operator methods, functional integration), rather all its properties are autonomous once its vacuum correlations or its characterization in terms of operator algebras has been settled. Therefore the first question is: does there exist a suitably defined quantum version of K-K with an autonomous meaning? This removes from the start manipulations involving Lagrangians as in [59].

There are two ways of formulating a QFT adaptation of K-K which would have an autonomous meaning, this freezing of one spatial coordinate leading to a "brane" and its compactification in the sense of "curling up" as envisaged by
string theorists.

The brane construction is mathematically well-defined. One may picture it as the thinning of a slab region in the sense that the spatial thickness of the slab goes to zero, whereas all the other infinite spatial extensions, as well as the extension of time, remains preserved. It is well known that operator algebra in an arbitrary thin tube around the time axis is equal to that of the subtended double cone, so the full time axis determines the entire global algebra. All the degrees of freedom of the original bulk description are also contained in the slab, never mind that this goes against classical intuition.

At first one’s instinctive reaction is that this looks fishy because the geometric symmetry group of the brane is smaller. But taking notice that the infinitely many appropriately defined fields with derivatives into the brane transform within themselves under the symmetry generators which lead out of the brane, one realizes that, in agreement with the preservation of the phase-space degrees of freedom, the full spacetime symmetry group is maintained and thus the strong relation between causality and covariance remains intact.

There is one case for which the spacetime symmetry group continues to act in the conventional way on the field variables of the lower dimensional QFT, this is the famous AdS$_{n+1}$-CFT$_n$ correspondence in which the CFT$_n$ represents a restriction to a brane at infinity. In that case the preservation of degrees of freedom prevents to have a physical theory on both sides of the correspondence. Either the AdS side has a physical cardinality of degrees of freedom which leads to an overpopulation on the CFT side, or the CFT side represents a physical QFT in which case the AdS$_{n+1}$ side is ”too anemic” in degrees of freedom in order to deserve the attribute ”physical”.

At this point it may be helpful to be more explicit about the degrees of freedom issue and to explain the pathological properties which arise from the presence of too many of them.

There is a second idea to reduce spatial dimensions which has been predominantly used by string theorists, this is the compactification of spatial dimensions and their subsequent pointlike limit (”curling up”).

In order for the compactification idea to have any intrinsic physical meaning beyond a formal game played with classical actions, one needs a structural argument which allows to execute the compactifying limiting process for a given model in an intrinsic operational manner. As mentioned before this excludes arguments based involving the Lagrangian setting of the kind used in [56]. The ideal method would be to start from the correlation functions or the uniquely associated operator formulation in a Hilbert space and to implement the compactification either directly on the correlation functions or in the operator setting. An implementation via spatial boundary condition has to argue against the mathematical fact that the change of the compactification radius leads to unitarily inequivalent representations which strictly speaking represent different

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36The action of the generators out of the brane resembles the action of an inner symmetry. Degrees of freedom and spacetime symmetries are inexorably linked (viz the AdS$_5$-CFT$_4$ correspondence). However projections onto a horizon (a nullsurface) are degree of freedom reducing.
Theories and not an intrinsic process.

The good news is that there exists such an intrinsic implementation of the compactification idea. This is possible with the help of the intermediate use of thermal physics which amounts to an inequivalent global representation of the same spacetime indexed net of operator algebra. It is well-known that the introduction of a KMS temperature amounts to compactify one coordinate of a euclideanized QFT which then becomes circular. The curling up process is implemented by the idea of a sequence of mutually contained subtheories localized inside a global ambient theory; this is the "open system" point of view which is very different from the simpler but nonintrinsic "quantization box" setting [1].

The execution of such open system limits is prohibitively difficult. Its general setting is the Nelson-Symanzik temperature duality. The best studied case (which recently has been placed into a modern context [57][58]) is that of two-dimensional superrenormalizable models.

**Theorem 1** (Nelson-Symanzik duality) The correlation functions of two-dimensional QFT whose spatial coordinate is periodic (e.g. lives on a circle with radius $R$) and whose time coordinate fulfills a $\beta$-KMS conditions state at imaginary time\(^{37}\) are equal to those in a dual theory where $R$ and $\beta$ are interchanged together with space and time.

Hence the classical idea of simply compactifying a noncompact coordinate compact "by hand" (imposing boundary conditions) has a flaw since the intermediate compactified quantum theories do not represent a sequence of mutually included theories with a compactification radius contacting to zero. In the other hand the formalism of open system, in which the smaller system is constructed as a genuine subsystem included into the bigger one, is insufficiently understood.

To some of the readers this discussion may sound a bit like nit-picking. But the maintenance of the hard fought-for representation theoretical consistency conditions which led to the d=10 infinite component pointlike ST does require the utmost care in descending in dimensions in order to avoid throwing out the baby (the consistency) with the bath water.

The obvious difficulty with any quantum compactification is the ubiquitous occurrence of localization-induced vacuum polarization. The only way to handle this problem is to find a multiplicative renormalization which keeps the limiting correlation finite.

In chiral theories for which the fields obey more general exchange algebras than fermionic/bosonic ones the Nelson-Symanzik temperature duality passes to a much richer selfduality which mixes the vacuum sector with the charged sectors via the Verlinde-Rehren matrix $S$. This suggests to implement the "curling up" as an infinite temperature limit.

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\(^{37}\)In terms of covariant pointlike fields the difference between a spatial periodicity and an imaginary time-like periodicity is in the different prescription of taking boundary values. In the Nelson-Symanzik duality these different prescriptions become interchanged.
The simplest QFT are higher dimensional conformal free fields. For a scalar neutral free $d=3+1$ dimensional conformal field at inverse temperature $\beta$ the two-point function is

$$\langle \varphi(x)\varphi(y) \rangle_\beta = \frac{\sinh 2\pi \frac{|x-y|}{\beta}}{8\pi \beta |x-y|} (\cosh 2\pi \frac{|x-y|}{\beta} - \cosh 2\pi \frac{|x^0 - y^0|}{\beta})^{-1}$$

It is easy to see that for $\beta \to \infty$ this function approaches the massless zero temperature function of a field with scale dimension $sd=1$ whereas the small $\beta$ limit at vanishing real time values behaves as

$$\langle \varphi(x)\varphi(y) \rangle_\beta \overset{\beta \to 0}{=} \frac{1}{8\pi \beta |x-y|}$$

which after liquidating the divergent $\beta^{-1}$ factor by multiplicative field renormalization is a two point function of a euclidean $d=3$ two-point function of scale dimension $sd = \frac{3}{2}$ of a massless free field. The last step namely the passing to a $d=2+1$ real time free field is best known in the form of analytic continuation, but there is also an intrinsic operational procedure.

Clearly this kind of dimensional reduction works for any dimension and it can be applied iteratively. The supersymmetry, which plays a crucial role in ST, is a symmetry unlike any other symmetry\(^{38}\). Unlike the Lorentz symmetry (and most other symmetries) which is spontaneously broken in thermal states, the supersymmetry is the only symmetry which "collapses" in a heat bath\(^{59}\) showing that supersymmetry is more like an unstable tuning between Fermions and Bosons than a stable symmetry. This raises the question whether supersymmetry is stable under dimensional reduction.

All this is applicable to ST which is described by a pointlike infinite component field. But there is a prize. Reducing dimensions in this way does destroy the delicate oscillator mechanism for generating a mass/spin tower with oscillator bridges between the different mass/spin levels. With other words the source-target picture which led to the 10 dimensional superstring is destroyed in any process of dimensional reduction and one does not really know why one first has to go to the 10 dimension superstring in order to arrive at a 4-dimensional consistent theory. What is the intrinsic property one wants to achieve in 4-dimensions which requires the detour?

An even bigger hurdle is the comprehension of the computational rules for interactions beyond the "tree approximation" represented by the dual model. These recipes have been conjectured by adjusting the Feynman rules to the situation of world-sheets instead of world-lines. But the string field is pointlike i.e. there are no world sheets in the target space so what should one make\(^{53}\)?

\(^{38}\) The physical origin of inner symmetries in QFT (a concept which does not exist in classical physics) is the DHR superselection theory\(^{1}\). All compact groups appear as potential symmetries except supersymmetry. This makes SUSY appear as an artificial junction of fermions and bosons by tuning coupling strength at a spacial value; it could be the explanation why a thermalization leads to a collapse of SUSY and not to the expected spontaneous symmetry breaking as in all other cases.
of those recipes? One would be in for a serious conceptual trouble if string amplitudes could be expressed in terms of operators and states as in any other accepted quantum theoretical activity in particular in Feynman’s perturbation theory.

In this case the tube rules would have to be taken as the definition and the dual model and the canonical quantization of the Nambu-Goto Lagrangian which inevitably led to pointlike objects must be rejected, which would amount to a clear position in a conceptually confused situation. But this is not the case; during 4 decades the efforts of the most renown string theorists have been unable to come up with an operational setting in a Hilbert space. Far from not having solved these problems, the string theorists have not even asked the questions because believing in an incorrect metaphor has prevented them to do so.

As we argued before QFT and with it its infinite component counterpart called ST have difficulties with the idea to generate internal symmetries from spacetime symmetries of QFT by a curling up process. We will argue that such a possibility is excluded on philosophical grounds since it would go against the very raison d'etre for the concept of internal symmetries whose purpose is to describe the relation between (neutral) observable algebras and their higher representations in charged sectors which combined together define the symmetry-carrying field algebras. For this it is useful to have a quick look at the history of the representation theoretical origin of internal symmetries and their relation to the structure of local observable algebras.

The concept of internal symmetries was always clouded by mystery ever since its inception via the SU(2) isospin of nuclear physics introduced by Heisenberg. The symmetry of classical physics is restricted to spacetime transformations. Since the concept of causal localization is fundamental to QFT it is natural to inquire whether the quantum adaptation of localization inherent in QFT could shed some light on inner symmetries. This is precisely what Doplicher Haag and Roberts set out to do in their research on the spacetime origin of the super-selection rules of local quantum physics which started at the end of the 60s and ended at the beginning of the 90 with a complete answer [52]. Not all programs which require such a large intellectual investment end with such a beautiful clear answer: by viewing QFT in terms of a dichotomy between (neutral) local observables and charge-carrying superselected states one delegates the issue of (particle) statistics, charge superselection rules and their incorporation into a canonical construction of a larger field algebra on which the symmetry acts as a global gauge group with the local observables re-emerging as the fixed point algebra under the inner symmetry.

In general the field algebra does not permit an immediate intuitive access since it involves unobservable (but extremely useful) operators, but fortunately

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39 The concept of inner symmetry in classical field theory does not exist in any natural way. But it is sometimes introduced by reading back properties from QFT into classical physics (similar to classical Fermions = Grassmann valued fields).

40 In this way the input into the Lagrangian quantization is understood as the output of a more basic autonomous theory.
its conceptual and mathematical structure is preempted in the structure of the
local observable net of algebras indexed by spacetime regions in a somewhat
hidden manner. By a sequence of conceptually quite interesting and profound
steps this unique field algebra (including the concrete inner symmetry group
which acts on it) can be constructed solely from the properties of its observable
projection. This is similar in spirit (but much more subtle in detail) to Marc
Kac’s famous saying “how to hear the shape of a drum”.

Although there is a deep connection between spacetime locality and inner
symmetries there is no support for a naive passing of curled up spatial coor-
dinates to inner symmetry indices. Certainly the above (only known) intrinsic
implementation via infinite temperature limits shows nothing in this direction.

Additional support against the string theorists view of spacetime and its
symmetries through the 10-dimensional target space of special class of chiral
theory comes from recent insights on space-time and the emergence of spacetime
symmetries in the algebraic setting. It turns out that all causally localized sub-
algebras of the global observable algebra are indistinguishable (unitarily equiv-
alent) independent of the localization regions; in technical terms they are copies
of the unique hyperfinite type $III_1$ von Neumann factor (“monads”). The mod-
ular localization theory (section 3) provides a relative positioning of monads in
terms of modular concepts [60] and that from an appropriate positioning of a
finite number (two for d=1+1, six for d=1+3) of monads in a common Hilbert
space one can derive the full content of QFT including the Poincaré symmetry
[61] which emerges from algebraically defined modular groups. Whereas space-
time symmetries are related to positioning of monads in a joint Hilbert space,
inner symmetries correspond to endomorphisms of operator algebra. Dimen-
sional reduction as well as supersymmetry is caught between two stools.

This casts considerable physical doubts on the target space construction of
spacetime symmetries. To avoid any misunderstanding, it is not the emergence
of a 9+1 dimensional infinite component field free wave function per se from
such a target construction which is being questioned, but rather the physical
rational behind it. The motivation for the old failed attempt for construct-
ing dynamical infinite component theories using generalizations of the Lorentz
group representation theory is at least comprehensible, whereas the conversion
of an inner symmetry component space of a chiral theory into a living space
space of higher dimensional relativistic theory is a weird requirement. Unfor-
nately mathematics allowed an exceptional positive answer in form of the
10-dimensional superstring; unfortunately because this was taken by the string
community as a revelation about the origin of spacetime instead of looking for
an explanation within the setting of chiral theories which are known to offer
a much greater richness at the place where in higher dimensional theories one
finds compact group inner symmetries. In this way we will probably never know
what really is behind the M-theory metaphor.

String theorists will probably retort that this choice is a fortiori justified by
the tube rules for the implementation of interactions. But since the tubes refer
to metaphoric and not genuine strings there is no reason whatsoever why one
should take for granted that transition amplitudes computed in this way can
reproduce those properties which any relativistic S-matrix describing particle scattering (independent of whether it comes from QFT or any other consistent particle scheme) must obey [9]. If string theorists succeed to derive these properties then they could start to claim that, even though all the physical arguments do not extend beyond metaphors, they nevertheless found by luck (but not as a gift of the 21 century!) an unusual prescription which assigns a consistent S-matrix to a special kind of infinite component field.

The prescription is very different from what one would obtain if one considers the infinite component field as the limit of finite component fields and applies the standard rules of causal perturbation theory. It is also different from what one would obtain if one were to use the string-localized description of section 5 (which each free field permits) for each irreducible component in the infinite component field and an extension of the causal perturbation theory to such objects.

7 Particle physics under the spell of metaphors

ST would never have come into being without the dual model and the latter would probably not exist without the Mandelstam representation for the elastic scattering amplitude. The fact that the Mandelstam representation is probably inconsistent with QFT does however not affect the dual model since the latter is a phenomenological tool (no connection to QFT required) whereas the former was thought to follow from locality and spectral properties. At the time of Veneziano’s discovery of the dual model, the peculiar mixture of mathematics of Gamma and Beta functions together with clever pedestrian tricks, as they are only available to experienced physicists, led many people to think that this model was unique in d=4. On the other hand the idea of uniqueness in the realization of a structural idea inevitably led in all cases to metaphoric thinking in the direction of TOE, starting with the S-matrix bootstrap. The production machine for dual models via Mellin transforms of conformal theories in any spacetime dimension should have turned down any mysticism in that direction. The imposition of unitarity and positive energy leads to uniqueness but, as we argued before, this is of doubtful value, since even if we were spared a stringy existence by recognizing the pointlike naure, we still would facte the problem of how to descend from 10 dimensions to our 4-dimensional flatland.

In order to make contact with reality one has to get rid of the excessive spatial dimensions in analogy to the Kaluza Klein model of classical field theory. It was shown in section 5 that neither of the two proposed methods (branes, curling up a compactified dimension) works. In the first case the cardinality of degrees of freedom stay the same a fact which is related to the preservation of the original spacetime symmetry with the brane-changing part of the group acting in an unfamiliar way [31]. The physical cardinality of the quantum matter in the bulk becomes unphysical in the brane (albeit mathematically consistent) leading to causal poltergeist phenomena and similar unwanted events. The curling up method on the other hand and the subsequent shrinking to a point
creates infinite vacuum polarization effects. There is also the problem why ST think that the properties they have implemented with so much effort (unitarity, positive energy) will remain unscathed; and if this is really the case, why it would not be better to understand the resulting object directly in 4 dimensions.

The most spectacular consequence of the metaphor about ST as a relativistic theory dealing with spacetime strings is the Maldacena conjecture [87] about a correspondence of a certain 4-dimensional supersymmetric conformal gauge theory with a ST in 5 spacetime dimensions in which 5 dimensions of the original 10 dimensions were compactified in the sense of Kaluza-Klein and became inner symmetries; following the standard parlance of string theorists this is the "gravity-gauge correspondence". This rather special conjecture became the focal point of the whole string community and led to an immense number of publications as no particle physics paper before; but none of these papers got anywhere near a proof or at least a plausibility argument.

What makes this sociological phenomenon appear similar to mass-psychosis as commonly observed in other human activities, is the fact that while most of these papers where written, there already existed a precise theorem on the AdS-CFT correspondence [62]. The method of its proof is in the best tradition of local quantum physics; instead of importing geometrical ideas it uses those autonomous localization and spectral properties of QFT which led to important structural theorems (TCP, spin-statistics, the DHR theory,..).

It shows in a mathematical rigorous way that the correspondence exists, but there is a physical hitch to it. If one starts from a 5-dimensional physical theory, the 4-dim. conformal theory is unphysical for the same reasons as the QFT on a brane in the previous section. So the correspondence theorem cannot not support the Maldacena conjecture which was viewed as corner stone of ST. Rehren’s theorem was shrugged off by the string community. A single person would be reluctant in ignoring such a theorem for fear of appearing ignorant, even if its conclusions are uncongenial to a proposed idea. But inside a sufficiently large community, such inhibitions are lost.

The saying "many people cannot err" is only valid in a restricted sense, namely if an individual arrives at an interesting result he should try to get the approval of some of his colleagues in order to minimize the possibility of an error. This step Rehren certainly passed.

To have the support of a worldwide community however diminishes the chances for correctness, because the drag to add an approving contribution to an ongoing worldwide fashion is much stronger than that for a critical assessment, in addition it is extremely helpful for increasing the impact and advances the career. This was already clearly visible at the time of the S-matrix bootstrap (when I was Lehmann’s assistent) except that in those days there still was a critical reaction (Jost,..); the Streitkultur of old Europe was still going strong and the S-matrix fashion disappeared in less than a decade. This is a reasonable lifetime for a proposal which did not contain a real conceptual error but was too vague in order to yield something useful. The almost 5 decade dominance of

\footnote{For a more detailed account see [9]}

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ST is to a large part the result of the disappearance of an internal Streitkultur which was replaced with connecting the rise of acceptance with the size of the community; this represents the new Zeitgeist which finds its stronger and better known manifestation in the financial capitalism and its markets.

This throws a somewhat different spotlight on Anderson’s critical remarks about ST in the introduction. Leaving aside whether it was hubris of some particle theorists which led in this uncritical way right into a new kind of particle theory without observational facts, even on purely theoretical grounds the theory has nothing to do which what it pretends to describe. Many particle physicists who have kept their common sense and tacitly rejected ST because they had the feeling of entering a surreal counter-world of particle physics, should feel vindicated. In fact this essay is intended to identify the cause of these gut feelings and provide them with a conceptual-mathematical expression. It is clear that it will not have an effect on hard core string theorists who live in their self-spun cocoon of reduced conceptual perception. A theory which substituted a metaphor for the most central property of local quantum physics namely localization, should actually create discomfort with any particle theorist.

To perceive the full extend of the philosophical aberration into which ST drove a sizable part of the particle physics community for several decades, the reader should take a look at the ”paradigmatic” new insights and ”revolutionary” upheavals about the new fundamental physics which one finds in books and essays as [63][64][65].

To close ranks between members of the community and to convince those who still waver, the message some of the string community leaders is that there is nothing to be gained looking outside ST; this is clearly the purpose behind their slogan ”there is no other game in town”. For many gifted and innovative non-stringy particle physicists who got the short side when competing with string theorists about positions, this slogan took on a literal existential meaning.

Leaving the difficult problem of an in-depth understanding of the action of the same Zeitgeist on different human endeavours as science, politics, money economy and cultural activities to sociologists, philosophers and historians of science, I will confine myself to some observations about the environment which facilitated the ascent of the string metaphor in particle physics.

The idea that particle physics may permit a description in terms of a unique theory (reductionist extremism), called a ”Weltformel” or a TOE, certainly preceded ST. Einstein was probably the first who proposed a generalized (classical) field theory containing his own gravity theory and all of that time known classical field theories. It had to fail because it was designed against the at that time already well established QT. The next attempt at a TOE, Heisenberg’s nonlinear spinor theory, gained for a short time the support of Pauli and had a strong local attraction around the MPI in Munich and . The reason may be related to the traditional hero worship of Germans, because at the first lecture tour of Pauli to the US, it did not survive the engaging critique by Feynman. The third shot for a TOE, namely the S-matrix bootstrap, emanated California. It is hard to imagine that it could have come from the east coast or middle west of the US since the number of religions, ideologies and new age life
styles, which it needed in order for a TOE to flourish, is more limited there. A first hand inside into the cultural surrounding of a TOE can be found in [60].

In fact the uniqueness of an appropriately formulated S-matrix theory was the driving force behind the S-matrix bootstrap, i.e. the predecessor of the dual model and ST, without which the latter would not have arisen. The bootstrap setting was not a perfect TOE, since there was no place allocated for gravitation, but on the other hand nobody worried about gravitation as a part of particle theory at that time.

Actually there was nothing metaphoric about its underlying S-matrix assumptions, the mysticism was solely in the expectation that these S-matrix principles will nail down a theory uniquely. In the middle of the 70s it became clear [67][68] that in d=1+1 the bootstrap principles produce an infinite set of elastic S-matrices which have unique field theories associated with them; one of the most fascinating discoveries about the inner workings of QFT. The ensuing important discovery of factorizing models of QFT via the bootstrap-formfactor program [69] attracted quantum field theorists (and plays a fundamental role in modern nonperturbative constructions of QFT), but was not even noted by the S-matrix bootstrap followers; for them the alternative seemed to have been either a TOE or nothing.

The same underlying algebraic structure appeared almost simultaneous in separate areas of mathematical physics. It became known under the name Yang-Baxter relation and already these names stand for two very different areas, Yang for two-dimensional scattering of a nonrelativistic n-particle system interacting via delta-functions and Baxter for the statistical mechanism of integrable 2-dimensional lattice systems. Even the field theoretic use at different places was not the same, in Saint Petersburg the main interest was integrability, whereas at the Landau institute, Berlin and Rio de Janeiro the leitmotiv of the research was to use two dimensional factorizing models as a theoretical laboratory to test ideas coming from higher dimensions under mathematically controllable conditions.

The uniqueness claim was based on the difficulty to solve the nonlinear bootstrap relations i.e. on the fallacious suggestion that something nonlinear which appears difficult, and for which one could not find any solution at the time, may be rather unique, if it has any solution at all; this kind of attitude towards nonlinear structures (example: Schwinger-Dyson equations, similar ideas in conformal QFT) was not new and was in each case contradicted by the existence of infinitely many solutions. Apart from the uniqueness ideology, the bootstrap project was founded on one extremely vague requirement called "maximal analyticity" (motto: impose analytic properties as the calculation proceeds until you run into contradictions), but since its ad hoc nature was so plainly evident, non of the concrete postulates caused any serious metaphoric confusions. Nevertheless it is clear, though not at the time of bootstrap, that the Zeitgeist was heading away from the laborious and precise approach of LSZ flanked by Wightman and Haag with the dispersion theory as the observational anchor.

There is one positive assertion in favor of the S-matrix bootstrap which should be mentioned; it placed for the first time an important property into the
focus of attention which before was occasionally observed in perturbation theory (and whose name refers to a graphical property of sums of Feynman diagrams of a given perturbative order): the *crossing property*. Among the many analytic properties following from the spectral and causality attributes of QFT, crossing is the only one which, although being derived from QFT, can be formulated solely on the (complex) mass shell. For this reason it plays an absolutely crucial role in the conceptual understanding of the field/particle interplay as well as in the nonperturbative construction of QFT via S-matrix properties \[25\][70].

These ideas, as well as their extension from the S-matrix to formfactors (matrixelements of fields between ket in- and bra out-states) have led to the first explicit construction of strictly renormalizable models of QFT within the before mentioned infinite family of 2-dim. factorizing models \[21\][30][42]. The obtained results may not have satisfied the S-matrix bootstrap community since their diversity represent the contrary of what one expects of a TOE. Nevertheless, measured against the absence of any existence proof of interacting properly renormalizable QFTs, this is a large step towards a better understanding of nonperturbative local quantum physics.

Although the interest in the bootstrap S-matrix program deservedly subsided with the ascent of gauge theories and the standard model, it did not fade out because of any incorrectness in its postulates; in fact all its S-matrix properties (apart from maximal analyticity and the illusion of a TOE) had a solid conceptual basis\[42\]. But the S-matrix bootstrap, as another previous attempt at a pure S-matrix approach, did not lead to interesting and trustworthy calculations on actual problems of particle physics, and hence it was no match to the rich new world of perturbative gauge theories. Such scientific explanations for the success of a theory are of course not entirely convincing since the sociologically much more successful ST did not contribute anything to its self-declared raison d’être, namely to link gravity with the other forces, and yet it flourished at least on a sociological level.

ST was born at the time when the bootstrap ideas with their explosive uncontrolled nonlinear structures created were loosing their attraction. People were looking for a setting in which nice computations could be formulated and carried through. The phenomenologically supported calculational opening started with the attempt of Veneziano \[72\] to find explicit realizations of the crossing property. The construction was generalized to arbitrarily many particles by Dolan, Horn and Schmidt in their work on the "dual resonance model" \[82\]. All these contributions were thought of as a consequence of a problem which was previously studied by Mandelstam, using a spectral representation for the 2-particle scattering amplitude whose validity, although not being deducible from QFT, was conjectured on the basis of generalizing established analyticity properties. The proven crossing property, as it can be rigorously implemented in constructions of soluble d=1+1 factorizing models, is a delicate interplay in which one-particle poles and cuts from the scattering continuum become in-

\[42\] The often heard objection that the principle of "nuclear democracy" contradicts the idea of quark/gluon confinement/invisibility is the result of a too naive understanding of both concepts.
termingled. The proof by quantum field theorists used powerful techniques of analytic functions of several variables as they emerged from the study of Wightman, retarded and time-ordered correlation functions in conjunction with the LSZ stationary scattering formula.

The solution which Veneziano encountered by using mathematical properties of Gamma and Beta functions, (later was referred to as duality) leading to infinitely many particle poles, is not the crossing symmetry of QFT but came out of mathematics. It was first formulated for the elastic scattering amplitude and later generalized to an arbitrary number of particles. Dual models with varying particle content were proposed [13]. All these dual models by It is important, despite all superficial similarities, to be aware of this distinction. Whereas all these dual models were originally constructed "by hand", using properties of special functions, nowadays we know that all of them originate as Mellin transforms from conformal QFT [31], in fact it is not difficult to the trained eye that behind the "operator representation" of the dual model in [13] is the Mellin transform of the chiral conformal theory of exponential potential of a multicomponent current theory.

Mellin transforms have no operator status on their own, the operator properties are limited to the untransformed conformal QFT. There are as many Mellin transforms as there are conformal QFTs; the infinitely many poles in a Mellin transform correspond to the infinitely many terms in the global conformal operator expansions [31]. The requirement of positivity imposed on the Mellin transform turns out to be extremely restrictive; the only solution corresponds to the d=10 superstring. This is somewhat easier to see in the string formulation (canonical quantization of the Nambu-Goto Lagrangian). I that setting one is dealing with an infinite component field for which in addition to the action of the Poincaré transformations which preserve the vertical mass-spin tower structure there are vertically acting oscillator operators which not only interconnect the different levels but also set the mass-spin spectrum. As mentioned before the construction of such an object was the (failed) aim of a group of people under the name dynamical infinite component fields before ST [20].

This raises the question what has the Mellin transform of a conformal field theory to do with crossing which refers to formfactors i.e. matrixelements of local operators between bra "out" and ket "in" particle states [43]. The answer is: nothing. In a way the reformulation in terms of ST removes the acuteness of this antagonism since a ST free field has no direct relation with a scattering amplitude. From the point of view of Regge trajectory phenomenology, duality was quite welcome, independent of its compatibility status with respect to crossing. On shell crossing can be shown in perturbation theory, but it is impossible to separate out the one particle pole contributions in such a way that crossing can be realized among the direct and exchanged one particle contributions. Crossing is always an extremely subtle interplay between poles and cuts i.e. between the full analytic structure of scattering amplitudes; it holds also in those cases in which there are no bound states.

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43 Scattering amplitudes are a special case.
It is legitimate to ask about the intrinsic quantum physical content of the reparametrization invariant Nambu-Goto Lagrangian, taking into account that the reparametrization invariance makes such a system classically integrable. For such systems one really should not apply the standard canonical quantization but rather abstract the Poisson bracket relations between the infinitely many conserved charges, convert them in the spirit of Dirac into algebraic relations for abstract operators, and represent the latter as concrete operators in a Hilbert space. This approach was successfully applied before to two-dimensional integrable QFT where it leads to a Poisson algebra structure for the infinitely many conserved "charges", which is then the point of departure for the construction of a quantum algebra.

Precisely this was Pohlmeyer’s starting point [74]. As expected, the resulting quantum theory had little to do with the kind of ST which resulted allegedly from the canonical quantization of Nambu-Goto like Lagrangians, in fact the two quantizations are inequivalent [75][76]. Pohlmeyer’s almost lifelong dedication to the real ST (described by the integrable reparametrization-invariant interacting Nambu-Goto form), after having made several important contributions to the foundations of QFT, is an illustration of perseverance in the defence of something which is mathematically and conceptually correct in the face of an ever swelling sea of publications in which the integrability of the Nambu-Goto system was ignored in favor of the canonical quantization of a model which is classically equivalent and which links up with the dual model.

It is hard to avoid the conclusion that a 40 years lasting domination of a theory, which in addition to its doubtful origin in the bootstrap S-matrix program created its own incorrect concepts, is a major calamity in the almost 80 year impressive history of particle physics. For physics the aspect of interpretation is absolutely crucial, whereas for a mathematician this is of minor relevance. Whether a geometric formalism refers to spacetime or to an inner symmetry space is of no relevance, the mathematics works the same in both cases. This explains why mathematicians are often impressed by ST. They love theories of physicists which have a somewhat metaphoric appearance and leaves some freedom to use it for inspiration in the pursuit of new mathematical theorems and to get to new subjects. The only point on which they are unrealistic is their belief that physicists are living in the best of all times; they would not understand if we tell them that they are creating their golden mathematical castles on our ruins.

The damage such a misinterpretation causes in particle physics is however considerable because (as was emphasized in section 4) a profound understanding of modular string localization is really of vital importance in any attempt to extend gauge theory [5]. The latter had a steep start in QFT when its importance for getting spin s=1 fields into the framework of a renormalizable action was recognized. But the resulting obviously incomplete setting did not really change for almost 40 years, and it is a legitimate question to inquire why it has sunk into stagnation.

One reason is fairly obvious, the present ghost formalism is designed to perturbatively construct local observables in terms of the standard perturbative
pointlike setting i.e. without any new investment into a revision of perturbation theory. All the important nonlocal (more precisely semiinfinite) physical objects as the electrically charged fields in QED and the question of the physical status of gluons and quarks are not described within the present perturbative gauge formalism. In the case of electrically charge fields there is at least a definition by hand which formally has been known since the time of Jordan 1935. This Dirac-Jordan-Mandelstam formula which describes a semiinfinite stringlike localized charge field is easily written down but to show that this object is renormalizable in every order is a prohibitively difficult and required to develop a new perturbative technology. Hence its construction, unlike that of the gauge dependent Lagrangian fields, is not part of the standard perturbative formalism. In the Yang-Mills case there is not even a formal proposal how semiinfinite stringlike field look in terms of Lagrangian variables.

In the case of massive vectorfields the situation is slightly better. The coupling of BRST ghosts is consistent with both the cohomological BRST rules and in the sense of renormalizability and power-counting (reducing the short distance dimension of the vectormeson+BRST from 2 to 1) under one condition: the massive vectormeson needs a scalar massive companion. This appears inches away from a crucial theorem: the locality principle + renormalizability → the Schwinger-Higgs screening mechanism; for a presentation of the history behind this concepts see. It is interesting to note that Higgs exemplified his idea in scalar QED (which has one parameters in addition to the mass of the complex charged field and the coupling to photons), because what he showed is precisely the existence of a different phase in which the charge becomes screened to zero, the complex scalar field loses half of its degrees of freedom by becoming a copiously produced real particle (the imaginary part serves to convert the photon into a vectormeson) which amounts to a charge-symmetry breaking. It is not clear whether Higgs thought about his mechanism in terms of a charged particle which was subjected to the process of complete screening, but Schwinger definitely had this very physical idea. He could not exemplify it in QED and hence he invented the two-dimensional Schwinger model. Swieca proved a structural theorem linking the appearance of massive vectormesons to charge screening.

The most remarkable aspect of the screening is that a partially nonlocal theory of string-localized charged fields becomes totally local in the screened phase. Whereas the particles corresponding to the semiinfinite string-like charged fields are infraparticles i.e. particle-like objects whose mass is somewhat blurred due to the presence of an “eternal” soft photon cloud whose energy can in principle be pushed below any energy resolution but not stripped of completely. The infraparticle property in momentum space is a consequence of the interaction which leads to the DJM string localization being the best possible. On the other hand the localization resulting from screening is pointlike i.e. the real part of the matter field which remains after screening is point-like.

\[^{44}\text{What is perhaps more important is the fact that there is no tensor-product structure with a clear notion of statistics.}\]
On the eve of new LHC experiments it becomes painfully clear that these ideas which were discussed more than 4 decades ago were not developed further and instead the metaphoric "Mexican hat" (which is part of the two-parametric coupling manifold of scalar QED) and more recently "God’s particle" took the stage. One expects that the generalization of the screening idea to the Yang-Mills situation also leads to a completely local theory, however the understanding of the nonlocal aspects in the phase corresponding to the unscreened Yang-Mills phase is a much harder problem (see section 4).

The return of metaphoric thinking in the 70s after its banning by Bohr and Heisenberg through the insistence in operational definition of observables in the beginnings of QM is a Zeitgeist phenomenon, and as such it would be too simple to see it solely as a consequence of the acceptance of ST. It is not an isolated event which suddenly arose in the context of the reformulation of the dual resonance model. Its seeds were already there at the time when duality was confused with a realization of crossing. It is conceivable that this mode of thinking will linger on even after ST has been given up as the result of its difficulties in delivering results.

8  A case study: the impact of superstrings in Germany

Traditionally particle theory in Germany has been quite strong on the conceptual and mathematical side. It has been claimed [24] that the discovery of quantum mechanics in a war-torn Germany was somehow related with the fact that its probabilistic aspect was especially in tune with the gloomy philosophical post world-war I mood expressed in Spenglers "decline of the west". But a more convincing explanation is that the sciences were hardly affected by the destruction of worldwar I, and the time of widespread political terror and racial persecution was still 15 years away. The situation after the world-war II was totally different; this time the moral and intellectual fiber was devastated, university live came to a standstill and some of the remaining physicists had left the country to work under less restrictive conditions.

Taking these conditions into consideration it was a small miracle that by the mid 50s particle theory was back on its feet in the Federal Republic. The work of Lehmann, Symanzik and Zimmermann (LSZ) who discovered the LSZ scattering theory and the work of Haag and Ruelle who showed that time-dependent scattering theory follows directly from the locality and the existence of a mass gap in the energy-momentum spectrum, were milestones in the understanding of the subtle connection between particles and fields. Lehmann developed together with Jost and a later important contributions by Dyson the so-called JLD representation which in turn was the basis of a rigorous derivation of a particle analog of the optical Kramers-Kronig dispersion which some time later was observationally verified. It was a well-balanced construction in that it combined highly conceptual aspects in the improvement of the subtle particle-field relation.
with useful formulas for scattering amplitudes in terms of vacuum correlations of fields. The conceptually well-founded derivation of dispersion relations and their experimental verification maybe considered unattractive by modern adherers of a TOE, but according to my best knowledge it is the only project on foundational problems in the history of particle physics which within in a reasonable amount of time was brought to a "mission accomplished" status.

There was a second similar line of research initiated by Rudolf Haag [1] and taken up and enriched by Hans-Juergen Borchers and others. Both explorations followed a similar leitmotiv, namely to get away from the quantization parallelism to classical physics and its limitation to perturbation theory.45 The liberation from classical quantization "crutches" was already on the mind of QFT Pascual Jordan, the protagonist of QFT [84], but then it was only a dream. Only in the hands of Haag and his collaborators it led to a profound understanding of mathematical structures which are outside the range of Lagrangian quantization as the understanding of spin&statistics and the superselection rules of generalized charges and their relation to global gauge symmetries from the structure of local observables [1] known under the name Doplicher-Haag-Roberts (DHR) theory.

After this resounding achievements in the early 70s, there were several other impressive contributions, all related to issues of locality of operator algebras, localization of states and thermal states on open systems. Although these results were not easily accessible to most particle physicist since they use novel (albeit very appropriate) mathematics, their importance was recognized by some, as it is obvious from the fact that the recognition of these achievements led to 3 Max Planck medals. The important discovery of the relevance of gauge theories and in particular of the standard model did not require any methodological revolution since it is an extension of the technology of renormalized perturbation theory of the 50s.

The differences in style between the LSZ kind of particle physics represented by LSZ and that of LQP represented by the Haag "school" were bigger than that of its scientific content. At the beginning it amounted mainly to a disparity of personalities. LSZ, in particular their spokesman Harry Lehmann personified the same engaging spirit as Pauli, Källén, Jost and others,46 who always put scientific truth ahead of sociological wellness and political correctness within the physics community; in contrast the people in the LQP project worked in a more withdrawn, if not to say ivory tower like setting.

Lehmann’s style (as LSZ spokesman) was that of critical engagement and if necessary confrontational but only against equals, never against novices. When Landau publically stated that there is no derivation of dispersion relation outside perturbation theory, Lehmann contradicted in public, but after that squabble

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45 The insight that the perturbative series are not even Borel convergent would have enforced this scepticism against any non-autonomous approach, but was not available in the early days of AQFT.

46 There was a strong personal affinity between Pauli and Lehmann which certainly played a role in Lehmann being able to take Wilhelm Lenz’s chair in Hamburg as one of Germany’s youngest professors.
they were on very friendly terms.

The favorite target of the LSZ critique was Heisenberg’s nonlinear spinor theory which for a short time was supported by Pauli. While on a speaking tour through the US (where his presentation of the nonlinear spinor theory) a critical encounter with Feynman led to a change of mind. However Pauli’s leaving the boat did not sink it; it did not change the atmosphere of veneration around the Max Planck Institute in Munich, but at least LSZ succeeded to impede its spreading to other places by preventing young newcomers to fall prey to ill-founded but seductive claims of famous physicists. One who came to the MPI at the end of the 50s and did not fall prey was Jorge André Swieca with whom I had the pleasure to collaborate for more than one decade. As a result of the situation at the MPI he contemplated leaving physics, apparently thinking that what he saw there was representative of particle physics at that time which it wasn’t, not even in Germany.

This points to a general problem in the sciences which has its origin in the enormous reputation which comes with the Nobel prize. It is more an exception than a rule that Nobel prize laureates are able to contribute fruitful ideas after they received the prize up to their old age. On the one hand they live under the pressure that this is what is expected of them, and on the other hand their ideas meet little criticism because of the Nobel prize aura around them.

Compare this episode with the actual situation of particle physics at the MPI Munich. With the helping hand of another Nobel prize laureate who later entered ST and became a member of the MPI advisory board, the entire particle theory department of the MPI became a home for ST and the TOE project. This time there was no engaging spirit which could have taken over the torch of public criticism from the previous LSZ generation; it was as if the personal softspoken non-engaging manner of Haag had changed into to an accommodating spirit of the entire LQP community.

Lehmann, like Pauli, Källén and Jost often used to compress their critique into sarcastic verdicts. Lehmann did not mince his words when, beginning at the end of the 50s, he criticized the bootstrap S-matrix approach, the Mandelstam representation and the dual resonance model salvaged from the former and the ST abstracted from it. During his time in active research he successfully prevented any of these speculative fashionable but unfounded proposals to take a hold in German universities. Unlike his collaborator and friend Res Jost, with whom he shared his critical views, he never formulated his critical arguments in the form of an article; they rather remained in the verbal realm.

Having attended as a student in Hamburg discussions among Lehmann, Jost and Källén and informal after seminar remarks, I had some problems at that time to understand why they all were so fiercely critical about the S-matrix bootstrap and those ideas which emerged in its orbit as the Mandelstam representation. After all educated speculations in certain situations contributed to the success of particle physics. Looking however with hindsight at the kind of particle theory ideas which resulted, one understands that their early doubts were justified.

If one has any doubts about the danger of ideas which lead to the formation
of a community of followers before they have been critically processed, one should study the demise of particle theory in the aftermath of the S-Matrix bootstrap, the Mandelstam representation and the later development via the dual model towards ST. Privily Lehmann and others may have expected that the popularity of some of those ideas was a transient fashion and over short or long people would find back to the kind of balanced physics where spectral representations are something to be either proved or dismissed.

During his active lifetime Lehmann used his prestige and influence in order to prevent particle theory getting stuck in senseless mind games. None of the aforementioned ideas had a basis in the principles underlying particle theory; in contrast to the derivation of dispersion relations which used proven (and not guessed) spectral representation, the mind games of the 60s and 70s did not make contact with physical reality, apart from grafting certain ideas whose relation to QFT was extremely doubtful onto experimental data which two years later were superseded by new data which brought that kind of phenomenology to an end.

But the LSZ community certainly underestimated the tenaciousness of ST to hang on, they believed too much in the self-correcting power of science and underestimated the strong influence of increasingly globalized sociological forces. They failed to see that by succeeding to create a community which accepted the move from the observationally contradicted phenomenological Regge trajectory setting of strong interactions to a highly speculative setting of a theory of quantum gravity at the Planck length, ST will have acquired a secure place at which it is immune against any critic. Since this was already 2 decades after its beginnings, it was too late for a foundational study as the one in this paper; the string theorists of the 80s by that time hardly knew their own history and their knowledge of QFT was in terms of computational recipes. Those who knew the QFT (especially the localization problematical) sufficiently were not interested in ST; as Lehmann they thought that ST is a transient phenomenon.

The quantum gravity coup which identified the string tension with the Planck length made ST experimentally inaccessible and the notion that there are theoretical principles to be met and the necessary knowledge to implement them was already in decline. Who will not concede that a "low energy effective approximations" of a theory, which has been proposed at distances of the Planck length, at the present state of computational art is too dubious for serving for an observational comparison?

Having thus reached immunity against the Damocles sword of experimental judgement which generations of particle physicists had to live under, the only remaining danger for the new mind game was critique from the side of physical principles and concepts. But as was shown in a previous section, the knowledge about conceptual structures in local quantum physics got lost with the string community and probably even beyond; we cited as evidence in section 5 the lost distinction between string- and point- like localization and the missed rele-

\footnote{The first phenomenological support for Regge trajectories and the dual model faded away with new scattering data arriving.}
vance of the notion of phase space localization in issues of correspondences and holographic projections.

After Lehmann’s retirement, when as a result of gradually failing health he had already withdrawn into private life and lost much of his political clout in the German particle physics scene, he expresses his doubts about the LQP community to stem the tide on many occasions. He worried about the self-centeredness and the lack of engaging spirit about what was going on in the particle physics mainstream as well as the active support ST received from some even some renown particle theoreticians (including Nobel laureates).

How correct he was in his assessment became obvious to me only some years later; three years before his death, on the occasion of one of my visits to Hamburg, he wanted to know from me what happened at the Berlin universities on the former DDR side in the confused aftermath of the German unification (which as far as the universities are concerned looked more like an "Anschluss"), when a group in ST was installed there. I found myself in the somewhat unpleasant situation to explain to my former advisor Harry Lehmann that none of the quantum field theorists and mathematical physicists at both of the academic institutions in Berlin had been asked for advice or had any influence on that decision.

This is somewhat indicative that when a group of researchers who starting in the 70s at the FU made important contributions to QFT is not consulted and not even informed about planned important changes. Normally physicists from nearby places who have contributed to the foundations, and hence have a lot of expertise, would either be directly invited to participate in the selection process for a new departments. But even Harry Lehmann, perhaps the internationally best known German physicist (at that time already retired) was informed. He was surprised that I, on a visit to Hamburg coming from Berlin, could not tell him either. We wondered why an area as ST, which produced not a single tangible physical result, was selected to present the new particle physics at one of the most important universities in the new old capital.

At first some people, including myself, thought that there was some foul play. But when I many years later saw that some of the best US universities hired people of a similar line of research it became clear to me that the millennium physics was precisely that tune of a TOE in form of ST and extra dimensions. In fact the distinction between sciences, politics and social ideas evaporates because there are easily recognizable cross connections which are part of the Zeitgeist: the millennium physics corresponding to the finance markets of the casino capitalism, and ST and the idea of a TOE relates to the trade with derivatives. Only as far as the crash goes, the Zeitgeist in the sciences lags somewhat behind.

Since science is an occupation of only a few, the scientific side of the breakdown will be less spectacular; a silent end of a more than 40 years old theories which has not led anywhere and, as we have shown in this essay, are build on misunderstandings of local quantum physics, will be the most probable event. This would be a pity, because the end of a theory which has captivated so many minds for such a long time contains valuable messages; in fact the message
contained in such a failure is, in my opinion as important as that in a successful theory. The people who will have the greatest interest to understand what was going on are naturally the historians and philosophers because to explain what has been going on and what was on the mind of the protagonists is their profession.

Human activities even those in the exact sciences were never completely independent of the Zeitgeist. In fact if there is any sociological phenomenon to which the frantic chase for a TOE finds it analog, it is the post-cold war reign of globalized capitalism with its "end of history" frame of mind [85] and its ideological support for insatiable greed and exploration of natural resources. It is hard to imagine any other project in physics which would fit the post cold war millennium spirit of power and glory and its hegemony claims in the pursuit of a these goals better than superST: shock and awe of a TOE against the soft conceptual power of critical thinking.

Whereas the post cold war social order has, contrary to its promises of a better life for mankind, accentuated social differences and caused avoidable wars and deep political divisions, the three decades long reign of the project of a TOE in particle physics has eradicated valuable knowledge about QFT and considerably weakened chances of finding one’s way out of the present crisis.

In the beginning of this section I argued against Foreman’s thesis claiming that the probabilistic aspect of QM was a result of the "demise of the west" gloom and doom spirit in post world-war I Germany. But on the other hand the relation between the "end of the history" capitalism and the glorious "end of the millennium" TOE in particle physics is something which would be hard to negate. ST with its lavish support is an activity where this analogy is most visible. The way in which the LHC research is publicized as the run for the "God’s particle" is another Zeitgeist-phenomenon. The theory stagnates since almost 40 years and now an experiment is expected to decide its fate.

With the death of Lehmann, Symanzik and Jost, the engaging style of research reached an end and metaphoric arguments became increasingly accepted. The sense for the importance of deriving observational accessible laws from established principles as in those previously mentioned cases (in particular the setting of dispersion relations), or for deriving results in a systematic and mathematically controllable way (renormalization theory of QED and the subsequent standard model) came to an end and the era of "everything goes" and of metaphors began to take roots with young people, in particular with those imaginative ones who were looking for excitement and adventure in particle physics. In this way ST came to play the role of the millennium theory in this new age.

Theoretical physicists as Klaus Pohlmeyer (see previous section), a theoretical physicist who stubbornly criticized ST by showing how the quantization of an integrable system as the Nambu-Goto Lagrangian is correctly done [74][76], became a tragic figure; as a listener in one of his seminars it was evident to me that the correct quantum theory of the Nambu-Goto Lagrangian was of little interest to people who found the metaphorical treatment based on canonical quantization which totally ignored the integrable structure much more relevant.
and exciting. Since the result did not meet the prejudices of string theorists, his lifelong work (which probably shares the fate with ST of being at odds with observations, but at least passed the conceptual-mathematical consistency test) remained unknown. The self-delusion of a TOE was stronger than the inner coherence of a theory of something which was at least conceptually consistent.

Compared with LSZ, the public perception about the LQP community was that of science in an ivory tower. Whereas the contributions of LSZ were in the center of particle physics, the profound enrichments of LQP were more peripheral as far as the day to day problems were concerned and only very few researchers succeeded to contribute to such problems. Any allegation of lack of engagement in the dispute about ST would be unfair if it would not also include autocriticism of one’s own role. The present work come much too late for having any influence. As mentioned before its content aims more at future historians and philosophers of physics.

The deep-rooted conceptual setting of the LQP research would have been the best antidote against the metaphoric spirit of ST; in particular since the Achilles heels of ST, namely localization, is the backbone of LQP. So how come that German particle physics succumbed to the string lure as exemplified in particular by the situation at the MPI in Munich and several other places where it took root, including at Hamburg which was the epicenter of the postwar renaissance of German particle physics.

The answer is outside the realm of pure science, it has to do with personalities and the culture of critical engagement with controversial subjects which enjoy the support of influential personalities, in short with sociological aspects. The LSZ school provided the backup of a solid conceptual platform for speculative excursions as well as for their critical evaluation.

This school (with a helping hand from Pauli, in his role as an apostate of Heisenberg’s nonlinear spinor theory) which successfully contained Heisenberg’s influence, did not exist any more when in more recent times the theory group of the Heisenberg MP institute in Munich, with a Nobel prize laureate in its advisory board, became a home of ST.

To make the irony of history of particle theory in Germany complete, slightly more than one decade after his death Lehmann’s chair went to a string theorist. There was apparently strong pressure from the side of the Desy theory on the theoretical physics department of the Hamburg University. As in times of royal rulers when every court had to have its own buffoon or oneirocritic, each reputable theory group at a high energy laboratory must have one string theorist. Unfortunately the Desy pressure was successful and Lehmann’s chair went to string theory.

With this step the circle about Lehmann’s legacy at Hamburg ended in a full turn. He started a successful campaign against Heisenberg’s nonlinear spinor theory. At the end he was helpless against a theory which is conceptually not less metaphoric and contradictory. His chair at the Hamburg University went to a string theorist and the Heisenberg Institute in Munich became the center of ST in Germany!

The present critique formulated in this article is by no means my private
intellectual hobbyhorse. At least some of the leading members of the LQP community have independent knowledge of most of the points, namely that ST wave functions are not string-like but point-like infinite component wave functions which contradict the application of Feynman inspired tube rules for transition amplitudes, as well as the strange metaphoric idea that one can embed a chiral QFT as a one-dimensional localized subtheory into a higher dimensional QFT as if it would be the same thing as a one-dimensional cord in a 3 dimensional quantum mechanics. Even those few string theorists who looked at the question of string localization \[22\] \[21\] noticed the pointlike nature and therefore could have explained to their fellow string theorists that should change terminology since their object is pointlike. But in order to save the string metaphor, or because they were confused about the issue of localization they proposed ”invisible strings” i.e. stringlike objects for which only one point on the string is visible. Quantum theory whose great achievement was the separation between classical and metaphorical aspects from intrinsic properties in Heisenberg’s notion of ”observables” was turned back from its feet to its head.

Localization and causality is the heart piece of LQP and the question arises why, in a recent survey article \[86\] in a joint book together with ST contributions, the authors do not come forward with a profound criticism and instead rather prefer to leave it at an easily overlooked remark that strings are pointlike without indicating what this implies about ST. String theorists have learned to live with such statements as long as no critical consequences are drawn, after all some of their own folks have come up with the statement that ST deals with strings in spacetime of which only one point is visible \[21\]. As long as the localization point lies on a string, the world of ST is in order.

The article missed the chance to engage the string theorists and preferred to maintain the ambience of their ivory tower instead of showing that string theorists are, conceptually speaking, ”would be” emperors without cloth. The idea that by abstaining from any profound scientific engagement with ST one can create a modus vivendi of mutual tolerance is naive since in the minds of ideologues of a TOE such behavior only underlines that their LQP opponents are obsolete since they are just repeating that strings are localized on a ”string-point” which they know from their own folks.

To be fair, there were valiant attempts to inject a critical note in discussions which arose in the tail of ST, but had their natural setting in the conceptually well founded QFT. One of those was Rehren’s \[62\] critical evaluation of the Maldacena conjecture when he demonstrated that the AdS-CFT correspondence is primarily a mathematical statement since the degree of freedom preservation inevitably makes on side physically pathological. But a mathematical theorem which listed heavily on the physical side, as the result of a mismatch with the physical phase space degrees of freedom \[77\] on one side of the correspondence i.e. the latter cannot link two physical QFTs; this is not a statement about a

\[48\] Only a radical conceptual revision at the end of which something entirely different that ST would emerge can assign a possible new mathematical/physical content. But this is not in the interest of string theorists and with an ill conceived physical motivation it is not interesting for non-string physicists either.
particular model but rather a structural property concerning a (rather radical) change of the localization concept of abstract quantum matter. No wonder that some string theorists who believed that these contributions are nothing more than a nuisance (since they go against what Maldacena conjectured) to their project began to refer to this work at conferences as "the German correspondence".

It would be hard to deny that in the times of the Pauli, Jost, Kallén and LSZ Streitkultur, feathers were often roughened, but the critical balance which was kept in this way was a great blessing for particle physics. Should social wellness be allowed to curtail conceptual clarity through a Streitkultur?

When the question comes up why many young people were lured into the metaphors of ST and why some of the important theoretical research institution had been taken over by ST crew, at least a partial answer is clear; a large part of the particle theory community, in particular the leading members of the LQP preferred social accommodation over scientific engagement. In contrast to their LSZ predecessors, they limited their critical standards to a well-defined region which included their ivory tower.

In this context it is worthwhile to comment on two statements from my LQP colleagues. One statement is that even if the foundation of what people are doing are metaphoric or confuse, they at least can communicate between them and there is always a certain chance that somebody finds something interesting. I do not know of any case which could support this point of view. Another statement which expresses a much stronger form of non-engagement and which protects conferences in which ST, the Maldacena conjecture, holography and the quark-gluon plasma are stirred together is the vernacular: "many people cannot err". I only know of cases where many people did err and the more people the greater and more subtle was the error. When I entered particle physics it was the S-matrix bootstrap and as time passed the errors increased with the size of the communities defending them and with ST the subtlety of the error and the size of the community are of such large proportion that incorrect theory cannot any more be disposed of. Since the engagement of those who know better is zero, the community which host such ideas will even grow because lack of engagement especially at a place dedicated to mathematical physics is interpreted as acceptance.

Whereas several aspects in this section (namely how ST took its roots, and in particular the fact that the knowledge of LQP is the ideal point of departure for a critical evaluation of superstrings) are specific for the situation in Germany, the dominance of ST in other counties followed a similar pattern. In most cases it started by a few renown members of the particle theory community beating the drums for superST as a TOE. What is more surprising is that those few, who had all the background and the intellectual capability to engage, refrained from doing so (this includes myself).

For a long time even sceptical minds as myself believed that the problem will take care of itself, the exact sciences represent a different mind-set from other human activities e.g. in the political domain. When after many years people realize that this is not what is happening they finally try to make the best out
of it, either by accommodation themselves with the ST or, if they are retired 
(and do not have a nice ST neighbor) they write articles as this one.

All jokes aside, the present situation in Germany is quite serious. After the 
QFT in Berlin was closed down at the beginning of this century, it is clear that 
there will be no continuation of QFT in Goettingen, and it does not take any 
visionary power that QFT in Hamburg, the place where LQP in Germany begun 
will also end. This is a pity because different from ST, the research on LQP never 
promised rapid success and after several decades of investment it has reached 
an interesting stage with many new results which promise to revolutionize QFT 
and particle theory.

9 Trying to get back on track: a particle theory 
without metaphors

The way out of the present plight is not simply a return to pre-string times. 
In exact sciences which support the concept of truth as opposed to other more 
opinion-driven human activities, having taken a wrong direction is not neces-
sarily a total loss. The comprehension of why and under what circumstances 
the misleading journey begun carries the chance of revealing a deeper insight 
into truth than that obtained by a direct path where the potential slips and 
some subtleties of the concepts were not appreciated. But such a situation 
would require a more serious study of the forgotten incomplete achievements 
and of those foundational insights into the building of local quantum physics 
which went largely unnoticed or got lost in the noise of a TOE. So one must 
find a way to break the unproductive alliance between the metaphoric bombast 
of a TOE and the longed for career and fame of our junior scientists. It is a 
myth that the development of the exact sciences follows its own intrinsic laws. 
Fashions and manifestations of the Zeitgeist are as influential as elsewhere.

As in any other human activity it is futile to hope for any auto-critical 
attitude from people who have dedicated a significant part of their scientific 
life to ST and its derivatives. A recent quotation of Churchill’s war endurance 
rallying cry: ”never, never,... give in”, which David Gross used to rally support 
behind ST precisely illustrates this point. This statement is quite an escalation 
from the previous ”the only game in town”. It is difficult not to agree with 
Anderson and understand such statements for what they really are: outbursts 
of arrogance which comes naturally with the conviction of having the keys to a 
TOE.

With the old Streitkultur between equals having been substituted by a propa-
ganda about a dominant monoculture of a TOE, particle theory became more 
representative of a Zeitgeist which led to the present hegemonic capitalism. 
There is the not unfounded fear that the partisans of ST could succeed to drive 
particle physics against a brick wall according to the tune of ”ST or noth-

ing”, the statements of some of its leading representatives sound like this. The 
Achilles heel here is the new generation; are they willing to study and extend
the still incomplete conceptual framework of QFT and put new life into the old Streitkultur, or do they prefer to follow the TOE-tunes?

There is no deficit of important problems and ideas how to solve them, which could end the 40 year conceptual stagnation about the standard model. QFT owes its survival and its present status as the most successful and universal of all physical theories to the methodological breakthrough obtained with renormalized QED. But even this impressive achievement of the quantized setting of Maxwell’s electrodynamics shows an incompleteness which is symptomatic for the points which will be raised in this concluding section. Whereas, apart from one interpretational issue going under the name of the problem of the ether, the classical Maxwell theory reached its conceptual closure already two decades after its conception, the fate of renormalized QED was less fortunate.

Even nowadays, more than 60 years after its discovery, its closure is still far away. When we talk about QED as a theory, we are using words in a much more loose sense than our forefathers about Maxwell’s theory at the beginning of last century. What really encourages to carry the conceptual problems behind gauge theory to their closure is the realization that these ideas, even in their present imperfect setting, have such impressive observational predictive power.

It is unfortunate that the misconception which presents ST as being string-localized has found a widespread acceptance as a fait accompli, because it shows that the issue of localization in relativistic QT which could decide about the fate of ST has been pushed to the wayside. As explained in section 4, ST is founded on the idea that the potentials $\Phi_{\mu}$ of an $n$-component chiral current can be interpreted as describing the locus of a string $X_{\mu}(\sigma)$ in a $n$-dimensional target space. This idea which insinuates the incorrect association to a relativistic position operator contradicts the intrinsic localization concept in QFT which was explained in section 5. Whereas the misunderstandings around the ether at the end of the 19th century had no effect on the mathematical structure of Maxwell’s theory (the outcome of the Michelson-Moreley experiment did not require a change in the Maxwell-Lorentz equations but only on their interpretation), the TOE at the turn of the millennium had a devastating still ongoing impact on particle theory which will reach far into the future of this century.

The worst aspect is not that in ST we are confronting a theory which is totally empty-handed with respect to observational checks because the existence of a consistent theory which generalizes the successful QFT would be a remarkable achievement even if at the end it is rejected by nature. Even the more than 50 years of its dominance can be tolerated if it would be conceptually consistent, or if at the end its inconsistency would lead to a conceptual enrichment as in the resolution of the ether problem a century before.

The seriousness of the confusion can be seen by looking at thousands of

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49 The ether postulate led to a wrong interpretation but had no effect on the form of the Maxwell equations (including their Lorentz symmetry) and the proof that they have nontrivial solution.

50 In order that the target space carries a unitary positive energy representation of the Poincaré group one has to admit spinorial target indices. The unique solution of these requirements is the $d=10$ superstring representation.
publication on ST as well as semi-popular publications on string localization in ST and QCD [53] including the inevitable drawings of open and closed spacetime strings in order to remove the last doubts about the spacetime meaning of strings.

With a "never give up" intransigence on the one side and the absence of the engaging spirit of the old Streitkultur on the side of those who know better on the other side of the fence, one has to be a notorious optimist in order to expect a change in the near future.

Particle physics and quantum field theory are presently in an upheaval. Many particle theorists look to new experiments at the LHC to lift them out of the present conceptual labyrinth which probably overburdens LHC. On the other hand there has been a very dedicated project for almost 5 decades which less than looking for discovering gems near the paths of great caravans has stubbornly pursuit one aim: the understanding the inner workings of QFT, despite all its incompleteness by far our most successful physical theory. This LQP project still did not lead to the closure of QFT, but it recently arrived at some remarkable results which are all related to modular localization.

After a long time of stagnation of gauge theory it became clear that its relation with modular localization (string-localization of potentials [5][88]) suggests an interesting and potentially important extension which is not limited to s=1 but applies also to higher spin. It also suggests a complete new look at the Schwinger-Higgs screening which is the better presentation of the Higgs mechanism. The already mentioned derivation of the crossing property of form-factors from modular localization is another result which together with the idea of wedge algebra generators [60][25] lead to the first mathematically controlled construction of factorizing models. Last not least it explains the relation of modular localization with thermal properties which originally were thought of as an intrinsic property of localization behind event horizons in curved space time. These ideas lead to a formula for "localization entropy" and a conjecture about a universal relation between heat bath- and localization-caused- thermal behavior. It is precisely this progress in modular localization which facilitates the critical evaluation of string theory although a direct criticism on specific claims of ST was always possible.

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