symmetry

Obituary

# Memories of Steven Weinberg (1933–2021)

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**Abstract:** Steven Weinberg, renowned particle theorist and Nobel laureate, passed away in July 2021. We discuss selections of his work on effective field theory, electroweak unification, and symmetry related topics. We then add a few memories of Weinberg at Harvard University then at the University of Texas, Austin.

**Keywords:** Steven Weinberg, particle theorist, electroweak unification, symmetry, memories

## 1. Introduction

Weinberg's legacy in theoretical physics is embodied within 300 papers and 17 books, of which 8 were technical and 9 were popular. According to his own writings, he regarded his two greatest accomplishments in rank order as (i) effective field theory, and then (ii) electroweak unification. His Nobel prize was awarded for (ii), not (i), but a similar complaint, if it is a complaint, could equally be made by another renowned particle theorist, C.N. Yang.

His CV:

Bronx High School of Science, graduated 1950 (as did Glashow).
Bachelor degree Cornell 1954; PhD Princeton (Treiman) 1957.
Postdoc: Columbia 1957–1959.
Faculty: Berkeley 1959–1966; MIT 1966–1973;
Harvard 1973–1982; UT-Austin 1982–2021.

In our opinion, his best books were:

Gravitation and Cosmology 1972 (technical);
The First Three Minutes 1977 (popular).
Both books remain fresh.

Steven Weinberg died on 23 July 2021 in Austin, Texas, the same day as Toshihide Maskawa in Kyoto, Japan.

We heard Weinberg give a few talks in the early 1970s before meeting him personally when we were a postdoc at Harvard for the 3 years 1978–1980. In 1982, he left Harvard for Texas and invited us to spend the year 1982–1983 with his group at UT-Austin. We were, therefore, his colleagues for a total of four years.

The adjectives about him which come to mind are he was both intellectually intense and competitive. He was not given to small talk and was always serious.

## 2. Effective Field Theory

Weinberg's most impactful work was provided by his monumental papers, e.g., [1–5], spread over more than a decade and a half, which developed the techniques and formalism of effective field theory. There is a lot of scientific honesty in the fact that although his standard model of electroweak unification (see below) was discovered in part by imposing strict renormalisability, Weinberg then spent far more time examining non-renormalisable theories and showing convincingly how in many cases they can be comparably as predictive.

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A simple effective field theory appears when we observe that when we add to a renormalisable Lagrangian $\mathcal{L}_{ren}$ which contains only terms of dimension $d = 4$, higher-dimension terms with $d = 5, 6, ....$ the full Lagrangian can be expected, under appropriate assumptions, to appear in the form

$$\mathcal{L} = \mathcal{L}_{ren} + \Sigma_i \frac{C_i^{(5)}}{\Lambda} \mathcal{L}_i^{(5)} + \Sigma_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{L}_i^{(6)} + ... \tag{1}$$

where $\Lambda$ is a cut-off scale much higher then the energies typically appearing in the theory described by $\mathcal{L}_{ren}$ alone.

For example, let us consider that the starting renormalisable Lagrangian is the standard model $\mathcal{L}_{ren} \equiv \mathcal{L}_{SM}$. In perturbation theory the standard model conserves lepton number $L$ and baryon number $B$. $L$ violation first appears in $d = 5$ terms which can generate Majorana neutrino masses so an appropriate cut-off could be a see-saw mass $\lambda \sim 10^{10}$ GeV. $B$ violation first appears in $d = 6$ terms so there an appropriate cut-off could be a grand unification scale $\Lambda \sim 10^{15}$ GeV. In both cases, the contributions will be suppressed by

$$\left( \frac{E}{\Lambda} \right)^{(d-4)} \tag{2}$$

where $E$ is a characteristic energy scale of the process in question.

Weinberg's starting point [1] was to show how current algebra results first obtained in the 1960s can be derived without the use of current algebra by the use of phenomenological Lagrangrians which satisfy the assumed symmetry principles and studying Feynman diagrams. Underlying this success is the fact that the most general quantum field theory has essentially no content except analyticity, unitarity, cluster decomposition and symmetry.

This procedure allows the calculation of corrections to the current algebra results which were found much earlier in the 1960s, including by Weinberg himself. Long before effective field theory, our own modest 1968 Oxford D.Phil. thesis under John Taylor showed how certain current algebra sum rules could be derived without current algebra by using analyticity in the form of superconvergence sum rules. In his next paper [2], Weinberg applied the effective field theory technique to gauge theories of grand unification as briefly mentioned *ut supra*.

In the early 1990s, buoyed by his successes with effective field theory in particle theory, Weinberg extended the use of effective field theory to nuclear physics. In 1990 [3], he calculated the forces between two or more nucleons from chiral symmetry breaking. Then, in 1991 [4], he extended this to include an arbitrary number of soft pions.

In impressive formal work [5] in 1996, Weinberg discussed when a gauge theory which is non-renormalisable in the usual power-counting sense can be nevertheless renormalisable in the sense that all divergences can be cancelled by a renormalisation of the infinite number of terms in the bare action. It was shown in [5] that this is true if the constraint on the bare action corresponds to the cohomology of the BRST transformations generated by the action.

The last paper [6] archived by Weinberg, only six months before his death, was a review of effective field theory. This supports the idea that he believed it to be his greatest legacy. Paper [6] is recommended to the reader as a beautifully written retrospective.

## 3. Electroweak Unification

To discover his electroweak unification [7], Weinberg adopted the $SU(2) \times U(1)$ gauge group proposed by Glashow several years earlier and combined that with the Higgs, or better Brout–Englert–Higgs, mechanism for spontaneous symmetry breaking. His specific contribution was to introduce the scalar Higgs doublet

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \tag{3}$$

and to allow the vacuum expectation value $< H^0 >$ of $H^0$ to induce spontaneous symmetry breaking of $SU(2) \times U(1)$ into the $U(1)_{QED}$ of quantum electrodynamics. The resultant theory contains three massive gauge bosons $W^{\pm}, Z^0$, together with the massless photon of QED and one physical scalar field, the Higgs Boson. Although Weinberg did not introduce any new particle because $Z^0$ and the Higgs Boson had already been successfully predicted, his choice of the dimension $d = 2$ doublet in Equation (3) was important. He could have added $SU(2)$ representations of higher dimensions $d = 3, 4, 5, ....$ but the choice in Equation (3) as a central part of the standard model has led to agreement with every experiment for the last six decades. This alone provides Weinberg with multi-century legacy. The choice allowed a prediction of the $M(W)/M(Z)$ mass ratio in terms of the electroweak mixing angle, in agreement with subsequent experiments.

At the time, in 1967, weak interactions were not at the forefront of particle theory research. We were a D.Phil. student in Oxford at the time when Weinberg published no less than six interesting papers in Physics Review Letters and we were recommended to read five of them, but never [7]. More generally, Ref. [7] was hardly cited at all until 1971. In 1971, a young Gerard 't Hooft created a sensation by demonstrating that such a theory is renormalisable on a footing with QED. At the end of [7], Weinberg had conjectured that renormalisability might survive spontaneous symmetry breaking but could not prove it.

As soon as 't Hooft's proof appeared in 1971, Weinberg [8] revisited the theory and showed how all the infinities cancelled in processes, such as

$$\begin{gathered} \nu + \nu \rightarrow W^+ + W^- \\ \nu + \nu \rightarrow \nu + \nu. \\ e^+ + e^- \rightarrow W^+ + W^- \end{gathered} \tag{4}$$

and remarked that the experimental discovery of the $W^{\pm}, Z^0$ gauge bosons would provide the best confirmation of the theory, as transpired in the 1980s.

Despite its slow start, Ref. [7] is now one of the two most cited papers ever in particle theory. It is the paper for which Weinberg shared the 1979 Nobel prize with Glashow and Salam.

## 4. Symmetry Related Topics

Weinberg published deep papers about symmetry which plays a central röle in particle theory. Of these, we shall discuss four [9–12] which were particularly impactful.

In 1962, one of the hottest topics was the Nambu–Goldstone theorem that spontaneous breaking of a global symmetry leads to the existence of massless spin-zero states. Nambu had reached this conclusion in 1960 from his deep understanding of the BCS theory of superconductivity, and went on a few years later to write related papers with Jona–Lasinio. Several months after Nambu, Goldstone provided a mathematical model which showed clearly how the N-G bosons arise for a Mexican-hat potential. Goldstone modestly claimed that his mathematical model had no physical application despite citing Nambu who had actually provided one: the lightness of the pion is a result of the spontaneous breaking of chiral symmetry. For decades, the massless or light states were called Goldstone bosons and only recently Nambu–Goldstone bosons. Fairest might be Nambu bosons. The problem for Nambu was a partially inscrutable writing style, not as perspicuous as that of Goldstone or indeed Weinberg. Nevertheless, the physics is there in Nambu. Despite this digression, we shall call it the N-G Theorem.

In [9], with Goldstone and Salam, Weinberg made a broad discussion of spontaneous breaking of global symmetries in quantum field theory with a view to proving the N-G theorem in the most general way possible. Indeed GSW succeeded to provide proofs, first within perturbation theory and then more generally. GSW [9] thus convinced the community in 1962 that for global symmetries the N-G theorem is correct. With the benefit of hindsight, we now know that when the global symmetry is replaced by a local gauged symmetry the N-G theorem no longer holds, as shown by Brout, Englert, and Higgs in 1964. Nevertheless, GSW was a timely and pivotal contribution to the emerging theory.

We proceed in chronological order to Weinberg's 1974 solo paper (the majority of his papers were solo) which discussed [10] spontaneously broken global and local symmetries at high-temperatures. In the majority of cases (there are a few exceptions) the symmetry will be restored at a critical temperature $T = T_C$ at which there is a phase transition. Weinberg considered a globally $O(N)$ symmetric scalar field theory with Lagrangian

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - P(\phi) \tag{5}$$

with a quartic polynomial potential

$$P(\phi) = \frac{1}{2}\mathcal{M}_0^2\phi_i\phi_i + \frac{1}{4}e^2(\phi_i\phi_i)^2 \tag{6}$$

in which $\phi_i$ is an n-dimensional vector representation of $O(n)$ and he is considering the spontaneous breaking $O(n) \to O(n-1)$.

The calculation at high-temperature $T$ reveals that the potential becomes

$$P_{eff}(\phi) = \frac{1}{2}\mathcal{M}^2(T)\phi_i\phi_i + \frac{1}{4}e^2(\phi_i\phi_i)^2 \tag{7}$$

in which

$$\mathcal{M}^2(T) = \mathcal{M}^2(0) + \frac{1}{12}(n+2)e^2T^2 \tag{8}$$

The critical temperature $T_C$ is that for which

$$\mathcal{M}^2(T_C) = 0 \tag{9}$$

which gives

$$T_C = \left(\frac{12}{n+2}\right)^{\frac{1}{2}}\frac{|\mathcal{M}(0)|}{e} \tag{10}$$

The result of the spontaneous breaking $O(n) \to O(n-1)$ is to produce $(n-1)$ massless N-G bosons and one massive scalar of mass $M(0)$. As usual, in the Mexican hat potential

$$m^2(T) = -2\mathcal{M}^2(T) \tag{11}$$

so that the critical temperature can finally be expressed as

$$T_C = \left(\frac{6}{n+2}\right)^{\frac{1}{2}}\frac{M(0)}{e} \tag{12}$$

Weinberg proceeded in [10] to analyze more examples including local $O(n)$ and global $O(n) \times O(n)$.

Although in the particle theory of $e^+e^-$. $e^-p$ and $pp$ colliders, we generally deal with $T = 0$, high $T$ becomes relevant in heavy-ion collisions and in the early universe where phase transitions play a central röle.

One of the perhaps questionable features of the standard model was the existence of elementary scalars. In 1976, Weinberg [11] attempted to invent a theory with no spin-zero fields and no bare fermion masses. With $N$ fermion types, not including color, such a theory possesses a $U(N) \times U(N)$ global symmetry which is broken intrinsically by electroweak interactions and spontaneously by strong interactions, the latter giving rise to pseudo-NG bosons. Such a theory mandates the existence of extra-strong interactions, now called technicolor, whose dynamics can be modeled by scaling QCD to an energy scale $\Lambda_{TC}$, higher than $\Lambda_{QCD}$. Weinberg [11] discussed some of the problems with making a realistic theory. Technicolor model builders have introduced extended technicolor which subsumes technicolor into a larger gauge group. Despite many attempts, it is fair to say that no realistic technicolor theory is presently known.

As a final example of Weinberg's work on symmetries, we discuss his 1979 paper [12] on the breaking of lepton (L) and baryon (B) number symmetries by higher dimensional operators in the standard model. L is first violated at dimension $d = 5$. B is first violated at $d = 6$. Weinberg classified the $d = 6$, $|\Delta B| \neq 0$ operators in the standard model using the notation for quarks

$$q_{i\alpha a L} \quad i = 1,2 \quad SU(2)_L; \quad \alpha = 1,2,3 \quad (color); a = 1,2,3 \quad (families). \tag{13}$$

and

$$u_{\alpha a R}; \quad d_{\alpha a R} \tag{14}$$

while, for leptons, he employed

$$l_{iaL} \quad i = 1,2 \quad (SU(2)_L); \quad a = 1,2,3 \quad (families) \tag{15}$$

and

$$l_{aR}. \tag{16}$$

There are six independent $d = 6$ B-violating operators, classified in [12] as follows

$$\begin{array}{rcl} \mathcal{O}^{(1)}_{abcd} & = & (\bar{d}^c_{\alpha aR} u_{\beta bR})(\bar{q}^c_{i\gamma cL} l_{jdL})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}, \\ \mathcal{O}^{(2)}_{abcd} & = & (\bar{q}^c_{i\alpha aL} q_{j\beta bL})(\bar{u}^c_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}, \\ \mathcal{O}^{(3)}_{abcd} & = & (\bar{q}^c_{i\alpha aL} q_{j\beta bL})(\bar{q}^c_{k\gamma cL} l_{idL})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{kl}, \\ \mathcal{O}^{(4)}_{abcd} & = & (\bar{q}^c_{i\alpha aL} q_{j\beta bL})(\bar{q}^c_{k\gamma cL} l_{idL})\epsilon_{\alpha\beta\gamma}(\underline{\tau}\epsilon)_{ij}.(\underline{\tau}\epsilon)_{kl}, \\ \mathcal{O}^{(5)}_{abcd} & = & (\bar{d}^c_{\alpha aR} u_{\beta bR})(\bar{u}^c_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}, \\ \mathcal{O}^{(6)}_{abcd} & = & (\bar{u}^c_{\alpha aR} u_{\beta bR})(\bar{d}^c_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}. \end{array} \tag{17}$$

The selection rule that $(B - L)$ is conserved follows from Equation (17), as do some other constraints which were discussed in [12].

Weinberg also considered $d = 5$ terms in the standard model:

$$f_{abmn}\bar{l}^c_{iaL} l_{jbL} \phi^{(m)}_k \phi^{(n)}_l \epsilon_{ik}\epsilon_{jl} + f'_{abmn}\bar{l}^c_{1aL} l_{jbL} \phi^{(m)}_k \phi^{(n)}_l \epsilon_{ij}\epsilon_{kl} \tag{18}$$

These terms violate lepton number and can contribute non-zero Majorana neutrino masses. We recall a discussion in 1979 at the Harvard faculty club when Weinberg said he had become convinced that neutrinos have non-zero mass.

For proton decay, the fact that the $d = 6$ operators in Equation (17) respect a global symmetry $(B - L)$ leads to the prediction that the leading proton decay is

$$p \to e^+ + \pi^0 \tag{19}$$

while the following decay should be suppressed

$$p \to e^- + \pi^+ + \pi^+ \tag{20}$$

If and when proton decay is observed, it will be interesting to confirm that the second decay mode is essentially absent.

We expect that Weinberg will be posthumously proven correct.

## 5. Harvard Particle Theory 1978–1980

The faculty were Weinberg, Glashow, Coleman, Glauber.
More junior were Georgi, Witten, Carlson, Bagger ...
Visitors included Cahill, Sudarshan, Baulieu, Frampton ...
This particle theory group was arguably the best in the world.

We sometimes occupied a desk in a corner of Sheldon Glashow's office and spent mornings and afternoons talking to him and, in between, lunch at the faculty club with Steven Weinberg. To write particle theory papers, such a stimulating environment was perfect.

Every Wednesday at noon was an unmissable gauge seminar.

A Couple of Memories from Harvard:

(1). At one gauge seminar, Weinberg gave a talk about SusyGUTs, including saying that new $d = 5$ operators were harmless with respect to proton decay. Georgi gently intervened with "That's an interesting phenomenological question". Weinberg looked surprised, thought for a while (he was not too quick, but deep), then said "Thank you Howard. You have saved me embarrassment". He had decided that the remark was correct. This was just one example of Weinberg's scientific honesty.

(2). At a faculty club lunch with Weinberg, the topic was: Does supersymmetry solve the gauge hierarchy problem? Steve pointed out that even with supersymmetry the hierarchy remains an input and is definitely not an output. Because of this, his conclusion was a categoric no. We sometimes thought about Steve's conclusion during the next decade when paper after paper stated the opposite. However, we never doubted that the correct answer is no. Weinberg was an exceptionally good particle theorist.

## 6. His Move from Harvard to Austin

In the 1970s, Louise Weinberg was teaching in a 3rd-rate college in Boston. Steve said privately that if Louise got a job at a first-rate place, he would move with her. In 1980, she received an offer from the top-ten law school at UT-Austin.

As a world-renowned physicist, Weinberg succeeded to negotiate a remarkable contract:

- He never needed to retire from UT-Austin;
- During his lifetime, no other faculty member in the College of Arts and Sciences at UT-Austin could ever earn more than 95% of his salary
  (UT-Austin's president was allegedly close to tears on this one);
- Least importantly, unlimited credit at the UT-Austin faculty club.

Until the last day, Weinberg harbored doubts about leaving Harvard. We recall sitting outside with Steve at a Harvard Square coffee establishment when he pulled from his briefcase an unsigned letter resigning tenure which he studied assiduously. It happened to be due that very day Wednesday, 30 June 1982. Steve said it was difficult to sign, the only time we ever saw Weinberg in doubt.

The period 1980–1982 provided Glashow with an opportunity to have some fun. Because of our relative youth, we have no idea how they were in 1950 when graduating together from the Bronx High School of Science but what we would say is that three decades later Shelly Glashow and Steve Weinberg had very different personalities. Shelly summarized the Weinberg situation by saying: "An irresistible force has met an immovable object!".

Glashow had a buddy at Texas A&M, a different campus from UT-Austin in the same state. He was an experimental particle physicist who had spent some time at Harvard, greatly appreciated SG and smoothly arranged a job offer to Glashow with double SW's new salary and equal to that of the Texas A&M football coach.

This accidental equality did not escape attention. A journalist from the magazine Sports Illustrated asked Glashow what he thought about being paid the same as a football coach. Shelly's quick and fun reply was: "At Harvard, I earn more than the football coach!"

## 7. UT-Austin 1982–1983

Weinberg was starting up his particle theory group in Austin. Each week there was a brown-bag lunch in Weinberg's capacious office at which students or visitors gave short presentations. He listened attentively and made comments and suggestions. He was a nurturer of young physicists and a good group leader.

For a few weeks, we worked on a research project together. It is so long ago we cannot remember the topic. That was the nearest we ever came to coauthor a paper. We are saddened that, with his passing, such coauthorship will never happen. We recall that Steve regarded our calculations as competitions and, at that time, he would give us a call at home, typically at 07:00 a.m. in the morning, to compare our separate progress.

A couple of memories from Austin:

(1). At one brown-bag lunch there were four talks, all on quite different topics. At a faculty party that evening, somebody asked Weinberg what the lunchtime talks had been about. What we noticed is that he could recall many peculiarly verbatim details and explain perspicuously every conversation, so we believe he had at least a several-hours echoic memory. Of course, everybody has an echoic memory of several seconds, otherwise discussion would be impossible.

(2). For one lunch at the faculty club there were a dozen particle theorists at Weinberg's table, mostly dressed far too sloppily. At a nearby table was the UT-Austin Board of Trustees, all elegantly dressed and looking affluent. We were sitting next to SW and, during a lull in the particle theory discussion, he looked over at the other table and said "I sometimes wish I had decided to become rich, rather than famous". We suspect Weinberg did not really believe that for one millisecond.

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