

Why the Cosmological Constant Is Small and Positive

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Within conventional big bang cosmology, it has proven to be very difficult to understand why today's cosmological constant is so small. In this paper, we show that a cyclic model of the universe can naturally incorporate a dynamical mechanism that automatically relaxes the value of the cosmological constant, including contributions to the vacuum density at all energy scales. Because the relaxation time grows exponentially as the vacuum density decreases, nearly every volume of space spends an overwhelming majority of the time at the stage when the cosmological constant is small and positive, as observed today.

One of the greatest challenges in physics today is to explain the small positive value of the cosmological constant or, equivalently, the energy density of the vacuum. The observed value, $7 \times 10^{-30} \text{ g/cm}^3$, is over 120 orders of magnitude smaller than the Planck density, 10^{93} g/cm^3 , as the universe emerges from the big bang, yet its value is thought to be set at that time. Even more puzzling, the vacuum density receives a series of contributions from lower energy physical effects, including the electroweak and quantum chromodynamics (QCD) transitions, that only become important at a later stage. Explaining today's tiny value requires a mechanism capable of canceling many very different contributions with near-perfect precision.

One long-standing hope had been to find a symmetry (*1*) or quantum gravity effect (*2, 3*) that forces the vacuum density to be zero. Another hope had been to find a relaxation mechanism driving it to zero in the hot early universe as the universe expands. These hopes have been hard to reconcile with cosmic inflation and, in any case, have been dashed by recent observations indicating that the vacuum density is small, positive, and very nearly constant (*4, 5*). Now it is apparent that one does not want a complete cancellation of the cosmological constant. And, in order for a relaxation mechanism to operate within the standard inflationary picture, the relaxation time must at first be much longer than the Hubble time, so inflation can take place; then much shorter than the Hubble time so that nucleosynthesis and structure formation can occur; and then, after that, much longer than the Hubble time again so that the vacuum density is nearly constant today, as observed. Despite many attempts, no simple and compelling mechanism has been found. The frustration has been enough to drive many physicists to consider anthropic explanations

(*6, 7*), in which one assumes that the vacuum density takes on all possible values in different regions of space, but that life is only possible in one of the rare regions where the vacuum density is exponentially small.

In this paper, we point out that a cyclic model of the type described in (*8, 9*) reopens the possibility of solving the cosmological constant problem with a natural, monotonic relaxation mechanism. In these models, each cycle consists of a hot big bang followed by a nearly vacuous period of dark energy domination, ending with a crunch that initiates the next bang. The duration of a cycle is typically on the order of a trillion years. There is no known limit to the number of cycles that have occurred in the past, so the universe today can plausibly be exponentially older than today's Hubble time and still form galaxies and stars as observed today. Within this cyclic framework, it is reasonable to consider mechanisms for relaxing the cosmological constant whose time scale is always far greater than today's Hubble time. The cosmological constant is exponentially smaller than one might have guessed on the basis of the big bang picture precisely because the universe is exponentially older than the big bang estimate, so the cosmological constant has had a very long time to reduce in value from the Planck scale to the minuscule value observed today. Furthermore, we will show that it is natural to have mechanisms in which the relaxation time increases exponentially as the vacuum density approaches zero from above, resulting in a universe in which nearly every volume of space spends an exponentially longer time in a state with small, positive cosmological constant than in any other state. This is in stark contrast to anthropic explanations, according to which the only regions of space ever capable of producing galaxies, stars, planets, and life are exponentially rare.

Dynamical relaxation: a worked example. As a specific example of a dynamical relaxation mechanism, we adapt an idea first discussed by Abbott (*10*) in the context of standard big bang cosmology [see also (*11*)]. In Abbott's model, the vacuum energy density of a scalar field gradually decays through a sequence of exponentially slow quantum tunneling events, relaxing an initially

large positive cosmological constant to a small value. In spite of some appealing features, Abbott found that the mechanism failed, as we will explain, within the context of a big bang universe, essentially because the relaxation occurs far too slowly compared to a Hubble time. In this paper, however, we show that the mechanism becomes viable within the cyclic universe picture.

Abbott's proposal introduces an axion-like scalar field, ϕ , coupled to the hidden nonabelian gauge fields through a pseudoscalar coupling $(\phi/f)F^*F$, with f representing some high energy mass scale and where F is the field gauge strength and F^* is its dual. The theory is assumed to have a classical symmetry

$$\phi \rightarrow \phi + \text{constant} \quad (1)$$

which is softly broken at low energies by various effects. Integrating out the gauge fields induces a potential of $-M^4 \cos(\phi/f)$, where M is the scale at which the gauge coupling becomes strong. [Fields of this type are commonly invoked to suppress charge-parity (CP) violation in the strong interactions (*12–14*) and are also ubiquitous in string theory.]

It is natural for M to be very small as a consequence of the slow (logarithmic) running of the coupling in a nonabelian gauge theory. For example, in QCD with six flavors, $\Lambda_{\text{QCD}} = M_{\text{Pl}} \exp[-2\pi/(7\alpha_{\text{QCD}} M_{\text{Pl}})]$ is about 100 MeV if the coupling strength at the Planck scale $\alpha_{\text{QCD}}(M_{\text{Pl}})$ is about 1/50. [Here and below, M_{Pl} is equal to $(8\pi G)^{-1/2}$.] In Abbott's model for the hidden axion field, M replaces Λ_{QCD} and is similarly expressed in terms of the relevant coupling to hidden gauge fields. For example, if the hidden sector were exactly like QCD, taking $\alpha(M_{\text{Pl}}) \sim 1/75$ would give $M \sim 10^{-3} \text{ eV}$, a viable value for our model. (Our choices are less extreme than those in Abbott's paper; in the 1980s, his goal was to obtain a very small vacuum density, whereas ours is to explain the observed value.)

The cosine potential breaks the continuous symmetry in Eq. 1 down to a discrete subgroup, $\phi \rightarrow \phi + 2\pi N$, where N is an integer. The discrete symmetry is also assumed to be softly broken by a term proportional to ϵ , resulting in a "washboard" effective potential:

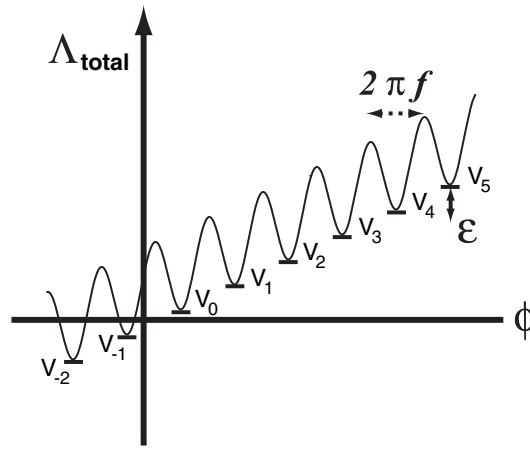
$$V(\phi) = -M^4 \cos\left(\frac{\phi}{f}\right) + \epsilon \frac{\phi}{2\pi f} + V_{\text{other}} \quad (2)$$

where V_{other} includes all other contributions to the vacuum density. (The linearity of the second, soft breaking term is inessential: Any potential will do as long as it is very gently sloping in the region of interest, around $V = 0$.) Provided that $\epsilon < M^4$, Eq. 2 has a set of equally spaced minima V_N , with effective cosmological constant Λ_{total} spaced by $V_N - V_{N-1} = \epsilon$ (Fig. 1). No matter what V_{other} is, there is a minimum with $\Lambda_{\text{total}} = V_0$ in the range $0 \leq V_0 < \epsilon$. Although ϵ must be chosen to be very small in order to account for today's tiny vacuum density, this choice is technically natural

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Fig. 1. The effective cosmological constant, Λ_{total} for the washboard potential defined in Eq. 2 can take discrete values depending on which minimum ϕ occupies. In the scenario presented here, the time spent in the lowest positive minimum is exponentially greater than the entire time spent in all other minima.



within the model because all quantum corrections to ϵ are proportional to ϵ . Hence, Abbott’s model is a self-consistent low-energy effective theory capable of cancelling contributions to the vacuum density coming from any other source.

In Abbott’s scheme, the smallness of the cosmological constant today is related through the relaxation mechanism to the smallness of the parameters M and ϵ in the potential $V(\phi)$. Effectively, the intractable problem of naturally obtaining an exponentially small cosmological constant is transmuted into a tractable problem of naturally obtaining small axion interaction parameters.

Abbott assumed that the universe emerges from the big bang with some large positive value of ϕ and quickly settles into a minimum with large positive V_N , driving a period of de Sitter expansion that dilutes away any matter and radiation. Over time the field ϕ then works its way slowly but inexorably downhill. In flat spacetime, the tunneling events would occur at a constant rate independent of N . However, once the effects of gravity are included, the tunneling rate becomes slower and slower as V_N decreases. As we shall see, the universe remains in the last positive minimum for a relative eternity compared with the time spent in reaching it. This is the basis for our claim that the most probable value for the vacuum density in the model is that of the last positive minimum.

Assuming the field starts high up the potential, $V_N \gg M^2 M_{\text{pl}}^2$, de Sitter fluctuations overwhelm the energy barriers and the field makes its way quickly downhill. But as V_N falls below $M^2 M_{\text{pl}}^2$, the barriers become increasingly important and the field progresses downward by quantum tunneling via bubble nucleation (15). Upward tunneling is also allowed but hugely suppressed in the parameter range of interest (16).

For simplicity, we shall focus on the parameter range $f^2/M_{\text{pl}}^2 \ll \beta < 1$, where $\beta \equiv \epsilon/M^4$ is the ratio of the difference between energy minima to the height of the energy barrier. In the semiclassical approximation, the rate for nucleating bubbles of vacuum energy density V_{N-1} beginning from the V_N phase is $\Gamma(N) \propto \exp[-B(N)]$, where $B(N)$ is the Euclidean action for the tunneling solution. In order to describe the scaling of $B(N)$ with N , we shall

neglect unimportant numerical coefficients and approximate $V_N \approx \beta N M^4$.

As ϕ tunnels toward minima with decreasing N , the nucleation rate decreases monotonically through three scaling regimes that match smoothly onto one another:

1) For $N > M_{\text{pl}}^2/(f^2\beta) \equiv N_{\text{HM}}$, the de Sitter radius is smaller than the bubble wall thickness, $\sim fM^{-2}$, and the relevant instanton is the Hawking-Moss solution (17). In this regime, $B(N)$ is proportional to N^{-2} .

2) For $N_{\text{CD}} < N < N_{\text{HM}}$, where $N_{\text{CD}} \equiv M_{\text{pl}}^2\beta/f^2$, the relevant instantons are of the Coleman-De Luccia type (15) and the thin wall approximation becomes increasingly accurate. The bubbles are in the scaling regime described by Parke (18), where the bubble radius is controlled by gravitational effects. In this regime, $B(N)$ is proportional to $N^{-3/2}$.

3) As N falls below N_{CD} , the bubble radius becomes much smaller than the de Sitter radius, and the instantons are well approximated by the flat spacetime bubble solution. Although gravitational effects increase the action by only a small factor in this regime, the correction is very important because B_0 is so large. The leading gravitational correction is given by

$$B(N) = B_0 \left(1 - \frac{3}{2} \frac{(V_N + V_{N-1})T^2}{M_{\text{pl}}^2 \epsilon^2} \right) \quad (3)$$

where the flat spacetime bubble action, B_0 , equals $(27/8)\pi^2 T^4 \epsilon^3$, with T as the wall tension. In a cosine potential this is $8M^2 f$. B_0 is an enormous number, $\sim 10^{110}$, for plausible parameters $f \sim 10^{14}$ GeV, $\beta \sim 0.1$, and $M \sim 10^{-3}$ eV. The gravitational correction causes the bubble action to decrease linearly with N in this final regime. Thus, as N approaches zero from above, the time spent at vacuum density V_N scales parametrically as $\exp[-B_0(N/N_{\text{CD}})]$, where N_{CD} is given above. For example, with our chosen parameters the time spent at the last positive value of the vacuum energy density is more than 10^{10110} times longer than the entire time spent before it.

The whole process ends when ϕ tunnels through to negative potential energy. Then, the negative potential causes the space within the bubble to

collapse in a time of order one Hubble time. (For this reason, it makes no difference whether the field could have tunneled further downhill or not because the region will collapse before it tunnels further downhill.) Space outside the bubble continues to expand from cycle to cycle, so there always remain regions with positive cosmological constant. Hence, the relaxation process we have described naturally leads to a universe that is overwhelmingly likely to possess a small positive cosmological constant, in agreement with observation.

Despite its attractive features, the proposal proves to be fatally flawed in a standard big bang cosmology setting, as Abbott himself pointed out, because of the “empty universe problem.” Each time the universe is caught in a minimum, it undergoes a period of inflation that empties out all matter and radiation. When a bubble is nucleated, its interior is nearly empty, too. At most, it contains an energy density, ϵ , and even if this is turned entirely into matter and radiation it is far too low to make planets, stars, or galaxies. In fact, whatever density does lie within the bubble is rapidly diluted away by the next bout of de Sitter expansion. The process continues; new bubbles are formed within the old, but at each stage the energy density is far too small to explain the observed universe. In effect, the problem is that the relaxation process is too slow for standard big bang cosmology, so that the universe is empty by the time the cosmological constant reaches the requisite value.

Cyclic model with dynamical relaxation.

With this thought in mind, we now turn to the cyclic model of the universe (8, 9). According to the cyclic picture, each big bang is a collision between orbifold planes (branes) along an extra dimension of space, as might occur in heterotic M-theory (19). A weak, springlike force draws the branes together at regular intervals, resulting in periodic collisions that fill the universe with new matter and radiation. After each collision, the branes separate and start to re-expand, causing matter and radiation to cool and spread out. Eventually, the matter and the radiation become so dilute that the potential energy associated with the interbrane force takes over.

In the low energy four-dimensional (4D) effective theory, the interbrane distance can be described by a modulus field, ψ , that moves back and forth along its effective potential. When the branes are far apart, the potential energy density is positive and acts as dark energy, causing the branes to expand at an accelerating rate and diluting away the matter and the radiation created at the bang. At the same time, the force draws the branes together, causing the potential energy density to decrease from positive to negative. As the branes accelerate toward one another, their expansion slows.

Ripples in the branes caused by quantum fluctuations are amplified by the interbrane force as the branes approach one another into a scale-invariant spectrum of growing energy density perturbations. The branes remain stretched out, though, and any matter and radiation within them remains dilute. So, after a period of a trillion years or so, the nearly

empty branes collide, creating new matter and radiation and initiating a new cycle of cosmic evolution. In dealing directly with the big bang singularity, the cyclic scenario poses new challenges to fundamental theory, and some aspects are still being actively debated (20–24). Here, we shall assume the cyclic picture is valid.

Now, let us suppose we add to this story the axion-like field ϕ and the associated hidden gauge sector as entities on one of the two branes. Surprisingly, although it was not invented for this purpose, the cyclic model has just the right properties to make Abbott's mechanism viable, leading to the prediction we have emphasized: a small, positive cosmological constant. Four features inherent to the cyclic model play a key role in rendering the combined model viable.

First and foremost, the cyclic model regularly replenishes the supply of matter and radiation, instantly solving the empty universe problem. Brane collisions occur every trillion years or so, an infinitesimal time compared with the eons it takes the universe to tunnel from one minimum to the next. So, between each step down the washboard potential, the universe undergoes exponentially many cycles. Each bubble that is nucleated fills with matter and radiation at the cyclic reheat temperature, $T_{\text{reheat}} \sim 10^8$ GeV or so (21), at each new brane collision. The value of ϵ is far smaller than the energy scale associated with the collision, so the washboard potential has little effect on reheating. Instead, it controls the low energy density, de Sitter-like phase of each cycle, ensuring the cycling solution is a stable attractor (9). For $f \gg T_{\text{reheat}}$, ϕ is only weakly coupled to the matter and radiation, and the reheating process does not significantly affect the evolution of ϕ .

A second essential element of the cyclic model is the orbifold (brane) structure. If ϕ were coupled to the usual 4D Einstein metric, its kinetic energy would be strongly blueshifted during the periods of Einstein-frame contraction. Instead of proceeding in an orderly manner down the washboard potential, it would be excited by the contraction and jump out of the minimum, accelerating off to infinity as the crunch approached. In the cyclic model, the behavior is quite different because ϕ couples to the induced metric on the brane, not the 4D effective Einstein-frame metric. The brane expands exponentially from cycle to cycle and never contracts to zero; only the extra dimension that separates the branes does that. Consequently, the kinetic energy of ϕ is red-shifted and diluted during every cycle, even during the phases when the extra dimension (and the Einstein-frame 4D effective scale factor) contracts to zero. Thus, ϕ remains trapped in its potential minimum for exponentially long periods until the next bubble nucleation occurs.

The reheating of the universe at the beginning of each cycle also does not excite ϕ because it is so weakly coupled. In fact, by causing the expansion to decelerate and hence suppressing the de Sitter fluctuations in ϕ , the matter and the radiation actually decrease the nucleation rate. The majority of tunneling events occur during vacuum energy

domination, which is the longest phase of each cycle.

A third advantageous feature of the cyclic model is that, because the homogeneity and isotropy of the universe and the generation of density perturbations are produced by very low-energy physics, there is no inflation and, hence, no need to tune the relaxation to be slow and then fast.

A fourth critical aspect of the cyclic model is that dark energy acts as a stabilizer. By diluting the density of matter and radiation and any random excess kinetic energy of the branes produced at the previous bounce, the dark energy ensures that the cycling solution is a stable attractor (9). When we add the washboard potential, the dark energy density depends on $V(\phi)$. The value decreases by ϵ each time a bubble is nucleated. As long as the dark energy density is positive, the cyclic solution remains a stable attractor. Once the sum becomes negative, the periodic cycling comes to an end. Most likely, the interior of the negative potential energy bubble collapses into a black hole, detaching itself from the universe outside it and ending cycling in that small patch of space, but the rest of the universe continues to cycle stably.

Putting these ideas together, the cyclic model and Abbott's mechanism are merged into a new scenario that greatly modifies both. In the combined picture, there are two fundamental time scales that govern the long-term evolution of any patch of universe: the cycling time, τ_{cycle} , and the time it takes to nucleate bubbles, τ_N . The latter increases exponentially as the universe tunnels from large N toward $N = 0$, and, during each of the stages we have described, τ_N is exponentially greater than τ_{cycle} . So, for each jump in ϕ the universe undergoes many cycles and many big bangs. When V_N is large, the vacuum energy density dominates the universe at an earlier point in the cycle compared with when V_N is small, before matter has a chance to cool and form stars, planets, or life. But, nothing happens to disrupt the evolution. The universe simply continues cycling as ϕ continues to hop down the potential, each step taking exponentially longer than the one before. Finally, V_N becomes small enough that structure begins to form. How big N is before this occurs depends on ϵ ; for our example above, galaxy formation occurs during the last few hundred steps or so. However, exponentially more time and more cycles are spent at $V = V_0$ than at any other value.

Discussion. We have focused on Abbott's particular mechanism, but we can extract from this case the conditions that are generally required: (i) a relaxation time much greater than today's Hubble time and (ii) a dynamics that collapses or recycles any regions with negative cosmological constant on a much shorter time scale. In our example, the relaxation time increases as the cosmological constant approaches zero, so that the system spends most of the time at the lowest positive value. However, it is also interesting to consider other parameter ranges or other forms for $V(\phi)$, including the pure linear potential invoked in the anthropic model of (6), which has no local minimum to be

fixed. In this model, the relaxation time decreases as the cosmological constant approaches zero from above. By introducing cycling and restricting attention to the past light cone of any observer, we find that most galaxies are produced when the vacuum density is smaller, but not much smaller, than the matter density.

In either example, our result is a universe in which the cosmological constant $\Lambda(t)$ is an ultra-slowly varying function of time t and in which virtually every patch of space proceeds through stages of evolution that include ones in which $\Lambda(t)$ is small enough to be habitable for life. It is interesting to contrast this situation with the anthropic picture, especially versions based on inflationary cosmology, for which the fraction of habitable space is infinitesimally small. All other things being equal, a theory that predicts that life can exist almost everywhere is overwhelmingly preferred by Bayesian analysis (or common sense) over a theory that predicts it can exist almost nowhere.

Although the relaxation time scale is far too slow to be detectable, the general picture we have suggested here can be falsified. First, because it relies on the cyclic model, it inherits the cyclic prediction for primordial gravitational waves (25). Second, one might look for other implications of having an exponentially long time for fields or couplings to evolve. For example, axions in QCD and string theory with $f \gg 10^{12}$ GeV are well motivated theoretically but ruled out in conventional inflationary theory because de Sitter fluctuations typically excite the field to a value where its energy density overdominates the universe today (26). Some propose resolving this dilemma, also, using the anthropic principle (27, 28), but then the same reasoning suggests that axions should contribute all or most of the dark matter density today (29). In the alternative picture we have presented, though, there is no inflation and axions are never excited. So, finding axions with large f and negligible density would be an embarrassment for the inflationary picture but would fit naturally in the picture outlined here. Similar considerations apply to other solutions to the strong CP problem (30) where a very long relaxation time may be useful.

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Regulatory Blueprint for a Chordate Embryo

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Ciona is an emerging model system for elucidating gene networks in development. Comprehensive in situ hybridization assays have identified 76 regulatory genes with localized expression patterns in the early embryo, at the time when naïve blastomeres are determined to follow specific cell fates. Systematic gene disruption assays provided more than 3000 combinations of gene expression profiles in mutant backgrounds. Deduced gene circuit diagrams describing the formation of larval tissues were computationally visualized. These diagrams constitute a blueprint for the *Ciona* embryo and provide a foundation for understanding the evolutionary origins of the chordate body plan.

During the past three decades, there has been remarkable progress in identifying the regulatory genes and signaling pathways responsible for the development of a variety of tissues and organs in worms, fruit flies, sea urchins, zebrafish, frogs, chicks, and mice. However, there are just a few cases where this information has been integrated to produce gene regulation networks embodying the functional interconnections among the genes responsible for a given developmental process. The best success has been obtained for the specification of endomesoderm in the pregastrular sea urchin embryo (1) and the dorsal-ventral patterning of the early *Drosophila* embryo (2). Significant progress has also been made on the specification of the “Spemann organizer” in the *Xenopus* embryo (3).

The ascidian *Ciona intestinalis* provides an ideal experimental system to elucidate gene regulatory networks. The ascidian tadpole shares a common body plan with vertebrates (4), including a notochord centered in the tail that is flanked dorsally by the nerve cord, laterally by muscle, and ventrally by endoderm. The mature ascidian larva is composed of ~2600 cells, and the genome contains only 16,000 genes (5). This genetic and cellular simplicity offers the promise of superimposing gene networks onto the behav-

ior of individual cells during specification and differentiation in early embryos. Such networks would provide a detailed understanding of complex morphogenetic processes and would establish a foundation for determining the evolutionary origins of chordate features in lower Deuterostomes (e.g., starfish and acorn worms) and their subsequent elaboration in vertebrates.

Here we present the systematic analysis of the 76 zygotic regulatory genes controlling *Ciona* embryogenesis during the time when the basic chordate tissues are specified and begin to differentiate. Particular efforts focus on the transcription factors and signaling components dedicated to the major tissues of the early tadpole. *Macho-1*, *Tbx6b*, and *ZicL* are expressed in the tail muscles (6–9); β -catenin and *Lhx3* in the endoderm (10, 11); *Fgf9/16/20*, *FoxA-a*, *FoxD*, *ZicL*, and *Brachyury* in the notochord (7, 12–14); and *Fgf9/16/20*, *Nodal*, *Otx*, and *GATA-a* in the CNS (15, 16). Gene disruption and in situ hybridization assays were used to create circuit diagrams showing the functional interconnections among the signaling pathways and regulatory factors governing the dynamic cellular interactions underlying the formation of the nerve cord, notochord, heart, and other key chordate tissues. These circuit diagrams constitute a blueprint for *Ciona* embryogenesis.

Regulatory codes for defined lineages.

Previous comprehensive in situ hybridization assays showed that the *Ciona* genome contains 65 genes encoding sequence-specific transcription factors (TFs) and 26 genes encoding components of cell signal transduction molecules (STs)

that are zygotically expressed between the 16-cell and early gastrula stages of embryogenesis (17, 18). Because of difficulties measuring zygotic transcription of genes expressed both maternally and zygotically, we excluded those genes exhibiting abundant maternal transcripts, thereby restricting the total to 53 TF genes and 23 ST genes (table S1). We do not regard the exclusion of maternal genes as a major limitation, because they are used to establish a regulatory prepattern in 16-cell embryos. The link between this prepattern and the establishment of definitive larval tissues is the major focus of the present study.

From the 16-cell to early gastrula (around 110-cell) stage, most of the blastomeres can be assigned a unique identity on the basis of the expression of specific combinations of TF genes (regulatory code; summarized in fig. S1). There is a close correspondence between establishing different regulatory codes and forming diverse cell lineages (Fig. 1). For example, the blastomeres that form the primitive gut (endoderm; A6.1, B6.1, and A6.3 at the 32-cell stage; and A7.1, A7.2, A7.5, B7.1, and B7.2 in 64-cell embryos) have slightly different regulatory codes during early cleaving embryos (fig. S2, A and B) but acquire identical codes at the early gastrula stage. The b5.3 and b5.4 blastomeres contain similar regulatory codes at the 16-cell stage. At the gastrula stage, descendants that give rise to nerve cord cells (b8.17 and b8.19) acquire a regulatory code that is distinct from their sister cells that give rise to epidermal cells (b8.18 and b8.20). The latter cells have a code that is similar to those of other epidermal cells, which indicates an inductive event at or before this stage. All lineages except the B7.5 blastomeres, which form the heart (trunk ventral cells) and anterior tail muscles, achieve clonal restriction before gastrulation. Thus, the hierarchical clustering of cell identities with similar regulatory codes accurately reflects cell lineages and the clonal restriction of cell fate and illuminates at what point key molecular interactions occur to establish a unique identity for each cell.

In order to define distinct neuronal cell identities, it was necessary to extend the analysis of regulatory codes beyond the early gastrula stage because of the complexity of neural cell types. Systematic in situ hybridization assays suggested that there are at least 13 distinct neuronal cell types composing the future central and peripheral nervous system at the late gastrula stage (Fig. 2, A and B;

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