Lectures on a tentative theory of large distance physics

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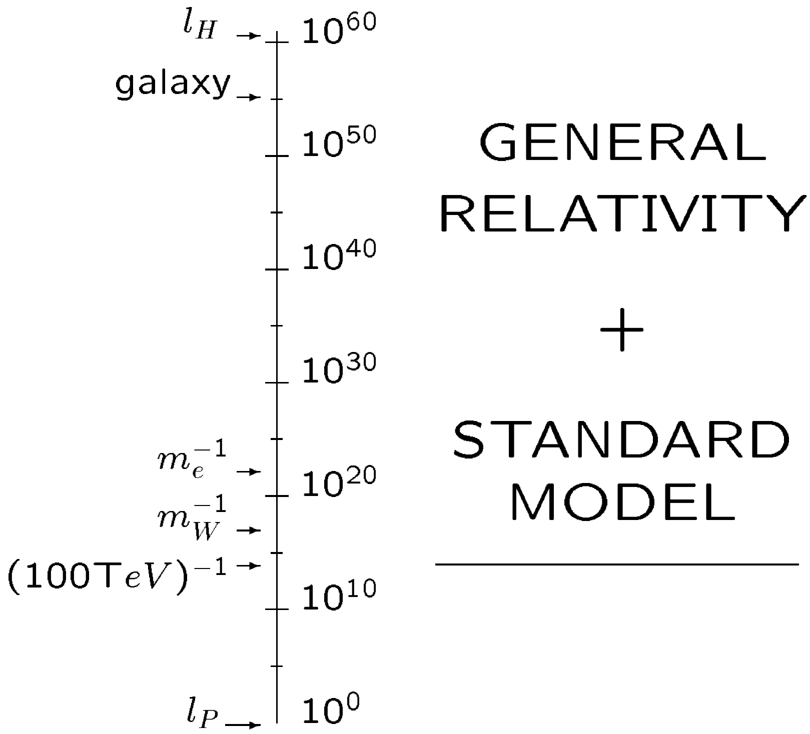
These lectures present an overview of a paper, *A tentative theory of large distance physics* (hep-th/0204131).

Many issues are left unmentioned here. Some are dealt with in the paper, or at least raised there. The interested listener or reader is invited to consult the paper.

These transparencies are available on the web at
www.physics.rutgers.edu/~friedan/Cargese2002/

Large distance physics

All physics that can actually be observed is at large distance in natural dimensionless units.



Only large distance physics can be checked.

For all practical purposes, a theory of large distance physics is all that is needed.

A theory of physics becomes credible first by explaining what is already known, by producing known theories in the appropriate regimes.

What is presently known about the laws of physics is summarized in one specific quantum field theory. (GR can be regarded as a QFT observed in the large distance classical regime.)

A theory of physics must:

- *produce* spacetime QFT at large distance
- produce a *specific* QFT, the Standard Model plus General Relativity, in every known detail.

Physics cannot be done by assuming QFT, then identifying a QFT by matching to an S-matrix theory.

QFT must be produced, not assumed.

S-matrix theory does not produce QFT.

S-matrix theory cannot produce mechanics.

The tentative theory

It is a comprehensive, self-contained theory of large distance physics (if correct).

Spacetime distances are numbers. The unit of distance is presumably near the Planck length.

The theory works entirely at large distance. It is not derived from small distance physics.

A mechanism, the λ-model, acts at all large spacetime distances L.

The λ-model is a certain 2d nonlinear model.

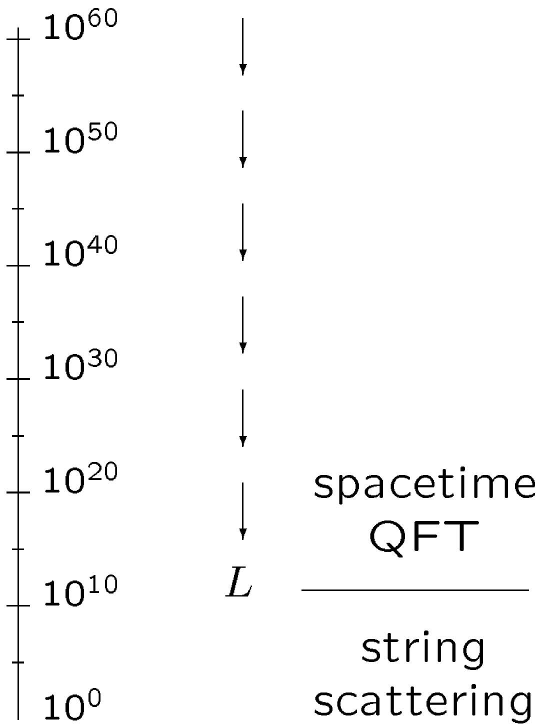
Its target manifold is, equivalently:

- the manifold of general nonlinear models of the string worldsurface at short 2d distance
- the manifold of spacetime fields (the spacetime metric etc.) at distances $> L$
- the manifold of background spacetimes for string scattering at distances $< L$.

At each large distance L, the λ-model produces two complementary descriptions of physics:

- a specific QFT at distances $> L$
- a specific effective background spacetime for string scattering at distances $< L$

L slides *downwards* from ∞.



The λ-model constructs physics *downwards* from the largest distances.

QFT is not derived from microscopic physics.

- It is a well-defined nonperturbative theory.

  It is not a hypothetical or conjectural theory.

  It is precisely determined by basic general principles.

  Nothing in the formulation is adjustable.

- It produces a specific large distance physics.

  QFT is produced, not assumed.

  QFT is not merely identified by matching to an S-matrix theory.

- It is an entirely new way to get QFT.

  Maybe new methods to calculate in QFT?

  Maybe novel effects at large distances?

Methodology

- First formulate a well-defined theory on basic general principles, capable of producing a specific large distance physics, capable of producing QFT.

  Then calculate.

- Now that a well-defined theory is formulated, the task is to investigate its structure.

  This is only the ground floor.

  Now: fill in details,
  develop methods of calculation,
  calculate QFT parameters,
  check if Standard Model is produced.

  These could be nontrivial tasks.

- It is only a tentative theory until checked.

  If right, it will stop being tentative.

  If wrong, it will also stop being tentative.

The general nonlinear model (Cargese, 1979)

A renormalizable 2d quantum field theory:

$$\int \mathrm{D}x \ \mathrm{e}^{-A(x)}$$

$$A(x) = \int \mathrm{d}^2 z \, \frac{1}{2\pi} \, h_{\mu\nu}(x) \, \partial x^\mu \, \bar{\partial} x^\nu$$

The field $x(z, \bar{z})$ is a map from the plane to a *compact, riemannian* target manifold.

$h_{\mu\nu}(x)$ is the metric coupling, a general riemannian metric on the target manifold.

In coordinates x^σ, the metric has Taylor series

$$h_{\mu\nu}(x) = h_{\mu\nu} + h_{\mu\nu,\sigma} x^\sigma + \frac{1}{2} h_{\mu\nu,\sigma_1\sigma_2} x^{\sigma_1} x^{\sigma_2} + \cdots$$

$$A(x) = \int \mathrm{d}^2 z \, \frac{1}{2\pi} \, h_{\mu\nu} \, \partial x^\mu \, \bar{\partial} x^\nu + \cdots$$

The $x^\sigma(z, \bar{z})$ are massless scalar fields in 2d, so are dimensionless.

The metric $h_{\mu\nu}(x)$ comprises infinitely many couplings, all naively dimensionless.

Renormalize $h_{\mu\nu}(x)$ at 2d distance μ^{-1}.

The renormalized metric coupling follows the renormalization group equation

$$\mu \frac{\partial}{\partial \mu} h_{\mu\nu} = \beta_{\mu\nu} = 2R_{\mu\nu} + \mathrm{O}(R^2)$$

2d scale invariance $\Leftrightarrow$ $\beta = 0$

$$0 = 2R_{\mu\nu} + \mathrm{O}(R^2)$$

Einstein's equation of General Relativity!

It became possible to imagine that spacetime physics might be explained using the apparatus of the general nonlinear model.

The target manifold of the general nonlinear model would be spacetime.

Perturb around a fixed point $\beta(h^{(1)}) = 0$

$$h_{\mu\nu}(x) = h^{(1)}_{\mu\nu}(x) + \delta h_{\mu\nu}(x)$$

$$\beta_{\mu\nu} = (-\nabla^\sigma \nabla_\sigma + \cdots)\, \delta h_{\mu\nu}(x) + \mathrm{O}(\delta h^2)$$

Expand in discrete eigen wave modes $\delta_i h_{\mu\nu}(x)$

$$(-\nabla^\sigma \nabla_\sigma + \cdots)\ \delta_i h_{\mu\nu}(x) = \gamma(i)\ \delta_i h_{\mu\nu}(x)$$

$$\delta h_{\mu\nu}(x) = \lambda^i\, \delta_i h_{\mu\nu}(x)$$

$$\phi_i(z, \bar{z}) = \delta_i h_{\mu\nu}(x)\ \mu^{-2}\, \partial x^\mu\, \bar{\partial} x^\nu$$

$$\delta A = \int \mathrm{d}^2 z\, \mu^2 \frac{1}{2\pi}\, \lambda^i \phi_i(z, \bar{z})$$

Perturb the scale invariant model by inserting

$$\mathrm{e}^{-\delta A} = \mathrm{e}^{-\int \mathrm{d}^2 z\, \mu^2 \frac{1}{2\pi}\, \lambda^i \phi_i(z, \bar{z})}$$

Wave modes become coupling constants λ^i.

ϕ_i has scaling dimension $2 + \gamma(i)$.

λ^i has scaling dimension $-\gamma(i)$.

$\gamma(i) = p(i)^2$

Anomalous dimensions $\gamma(i)$ are geometrical, related to spacetime wave number $p(i)$.

At short 2d distance $\Lambda^{-1} \ll \mu^{-1}$, the model is parametrized by running coupling constants

$$\mathrm{e}^{-\delta A} = \mathrm{e}^{-\int \mathrm{d}^2 z\, \Lambda^2 \frac{1}{2\pi}\, \lambda_r^i\, \phi_i^\Lambda(z,\bar{z})}$$

$$\Lambda \frac{\partial}{\partial \Lambda}\, \lambda_r^i = \beta^i(\lambda_r) = \gamma(i)\, \lambda_r^i + \cdots$$

$$\lambda_r^i = (\Lambda/\mu)^{\gamma(i)}\, \lambda^i + \cdots$$

Define $L^2 = \ln(\Lambda/\mu)$

$$\lambda^i \;=\; \mathrm{e}^{-L^2 \gamma(i)}\, \lambda_r^i \;=\; \mathrm{e}^{-L^2 p(i)^2}\, \lambda_r^i$$

λ_r^i is *irrelevant* if, say, $\mathrm{e}^{-L^2\gamma(i)} < \mathrm{e}^{-400}$ which is $\gamma(i) > 400/L^2$ or $p(i) > 20/L$.

The coupling constants of the model are the spacetime wave modes at distances $> L$.

L acts as UV cutoff distance in spacetime.

The manifold of general N-L models is finite dimensional (and depends on L).

The general N-L model in string theory

The general N-L model constructs the string worldsurface in a curved spacetime (a more complicated general N-L model, more 2d fields, more spacetime fields as couplings).

target manifold is background spacetime

$\beta = 0$ is a string theory consistency condition (but still *not* a dynamical equation).

The solutions of $\beta = 0$ are (essentially) the manifold of 10d Calabi-Yau spaces.

String theory failed as physics because of the manifold of possible background spacetimes (free parameters, massless particles).

This is an IR failure. The marginal coupling constants, $\gamma(i) \approx 0$, are IR, at $p(i) \approx 0$.

Formal task:

Determine the background spacetime.

The manifold of spacetimes

$$=$$

$$\Big\{\text{models of the heterotic worldsurface}\Big\}$$

$$\approx$$

$$\Big\{\text{10d compact Calabi-Yau spaces}\Big\}$$

The $\{\lambda^i\}$ are the coupling constants after GSO projection, the spacetime wave modes of

- the spacetime metric
- the gauge fields
- the scalar fields (including dilaton)
- the antisymmetric tensor field
- the chiral fermion fields

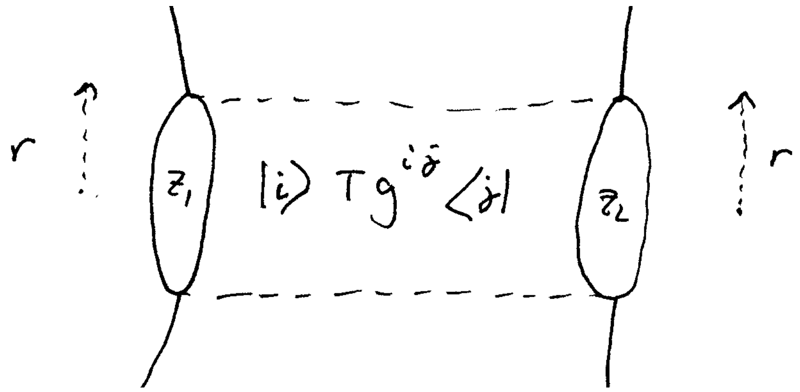
The string theory is tachyon-free:

All $\gamma(i) \geq 0$.

The rg flow drives to the fixed manifold, $\beta = 0$.

There are no relevant coupling constants λ^i. All are either marginal, $\gamma(i) \approx 0$, or irrelevant.

Handles in the worldsurface



$T\,g^{ij}$ is the gluing matrix for states i, j flowing through the ends of the handle ($T \propto g_s^2$).

effects of handle = non-local insertion

$$\frac{1}{2}\int \mathrm{d}^2 z_1\, \mu^2 \frac{1}{2\pi}\, \phi_i(z_1, \bar{z}_1) \int \mathrm{d}^2 z_2\, \mu^2 \frac{1}{2\pi}\, \phi_j(z_2, \bar{z}_2)$$

$$T g^{ij} \int_{\mu\Lambda^{-1}} 2\, \mathrm{d}(\mu r)\, (\mu r)^{\gamma(i)+\gamma(j)-1}$$

Λ^{-1} is 2d cutoff distance on r.

$\gamma(i) \approx 0 \Leftrightarrow$ log divergence

manifold of spacetimes $\Leftrightarrow$ log divergence

The IR failure of string theory is a technical pathology of the worldsurface.

The kernel of the non-local insertion is

$$Tg^{ij} \int_{\mu\Lambda^{-1}} 2\,\mathrm{d}(\mu r)\,(\mu r)^{\gamma(i)+\gamma(j)-1}$$

where $Tg^{ij} = 0$ unless $\gamma(i) = \gamma(j)$

To extract the Λ^{-1} dependence, integrate up to some 2d distance Λ_1^{-1} (arbitrary choice)

$$Tg^{ij} \left[\frac{(\mu\Lambda_1^{-1})^{2\gamma(i)} - (\mu\Lambda^{-1})^{2\gamma(i)}}{\gamma(i)} \right]$$

For small $\gamma(i)$, this is the string propagator

$$Tg^{ij} \left[\frac{1 - \mathrm{e}^{-2L^2\gamma(i)}}{\gamma(i)} \right]$$

with IR cutoff at $\gamma(i) = L^{-2}$, $p(i) = L^{-1}$.

The 2d cutoff Λ^{-1} imposes an IR cutoff in every string channel.

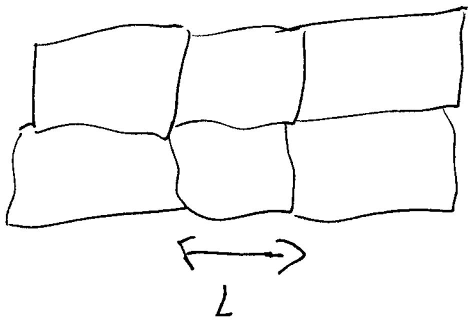
L is the IR cutoff distance for string scattering.

Realist version of string scattering ($\Lambda^{-1} \neq 0$)

L is IR cutoff distance on string scattering.

L is UV cutoff on the coupling constants λ^i.

Picture spacetime tiled by cells of size L, which are experimental regions for string scattering ($\beta = 0$ at spacetime distances $< L$, all the irrelevant λ^i are zero).



The nearly marginal coupling constants λ^i are the spacetime wave modes at distances $> L$ describing the environment (the experimental apparatus). They have $\beta \neq 0$ so act as sources and detectors for strings.

String scattering is always at relatively small distance in a real physical environment.

The idealized pure S-matrix version of string scattering is at $\Lambda^{-1} = 0$, $L = \infty$.

Taking spacetime to be compact riemannian is being ultra-careful to control the IR. Wave modes are discrete. Discrete zero modes give the log divergence.

Now consider a macroscopic spacetime, (dimension n, large volume V)

$$T = g_s^2 V^{-1} \qquad T g^{ij} = g_s^2 \, (V^{-1} \, g^{ij})$$

Discrete sums over wave modes become momentum integrals

$$\begin{aligned}\sum_{i,j} T g^{ij} &= \sum_{p(i)} \sum_{p(j)} T \, \delta_{p(i),p(j)} \\ &= \int \mathrm{d}^n p(i) \int \mathrm{d}^n p(j) \; g_s^2 \; \delta^n(p(i) - p(j))\end{aligned}$$

writing only $p(i)$ for $i = (p(i), \cdots)$

The string propagator becomes

$$g_s^2 \;\; \delta^n(p(i) - p(j)) \;\; \left[\frac{1 - (\mu\Lambda^{-1})^{2p(i)^2}}{p(i)^2} \right]$$

Take $\Lambda\partial/\partial\Lambda$ to find the 2d scale dependence

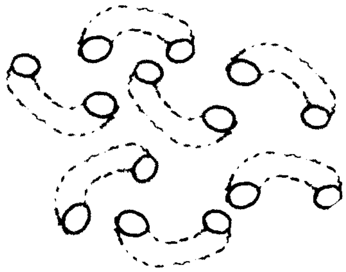
$$g_s^2 \;\; \delta^n(p(i) - p(j)) \;\; \left[2 \, \mathrm{e}^{-2L^2 p(i)^2} \right]$$

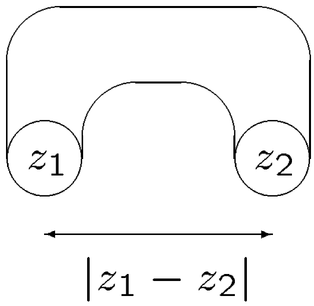
The dependence on Λ^{-1} is at distances $> L$.

The log divergence is pushed to $L = \infty$ in the idealized pure S-matrix theory, $\Lambda^{-1} = 0$.

Local handles

Local handles change the 2d short distance structure, which is the large distance physics.





Strategy: Add a local mechanism to cancel the local handles. Keep 2d locality for sensible small distance string scattering. Non-local handles are made of the dressed worldsurface.

The separation $|z_1 - z_2|$ is used to extract the Λ^{-1} dependence naturally, without an arbitrary choice of another 2d distance Λ_1^{-1}.

effects of local handle = bi-local insertion

$$\frac{1}{2}\int \mathrm{d}^2 z_1\, \mu^2 \frac{1}{2\pi}\, \phi_i(z_1, \bar{z}_1) \int \mathrm{d}^2 z_2\, \mu^2 \frac{1}{2\pi}\, \phi_j(z_2, \bar{z}_2)$$

$$T g^{ij} \left[\frac{(\mu\,|z_1 - z_2|)^{2\gamma(i)} - (\mu\Lambda^{-1})^{2\gamma(i)}}{\gamma(i)} \right]$$

The kernel in the bi-local insertion is

$$T g^{ij} \, (\mu \Lambda^{-1})^{2\gamma(i)} \, \left[\frac{(\Lambda \, |z_1 - z_2|)^{2\gamma(i)} - 1}{\gamma(i)} \right]$$

Cancel the local handles by inserting sources

$$\mathrm{e}^{-\int \mathrm{d}^2 z \, \mu^2 \frac{1}{2\pi} \, \lambda^i(z,\bar{z}) \, \phi_i(z,\bar{z})}$$

which fluctuate with gaussian propagator

$$\left\langle \lambda^i(z_1, \bar{z}_1) \;\; \lambda^j(z_2, \bar{z}_2) \right\rangle =$$

$$T \, g^{ij} \, (\mu \Lambda^{-1})^{2\gamma(i)} \, \left[\frac{1 - (\Lambda \, |z_1 - z_2|)^{2\gamma(i)}}{\gamma(i)} \right]$$

Handles are at 2d distances $|z_1 - z_2| > \Lambda^{-1}$ (where the kernel is positive).

λ-fluctutations are at $|z_1 - z_2| < \Lambda^{-1}$
(where the λ-propagator is positive).

Gaussian λ fluctuations cancel a gas of independent local handles. Interactions are needed to account for collisions of handles.

At $|z_1 - z_2| \approx \Lambda^{-1}$, the λ-propagator is

$$\approx -T\, g^{ij}\, (\mu\Lambda^{-1})^{2\gamma(i)}\ \ln(\Lambda^2\, |z_1 - z_2|^2)$$

The $\lambda^i(z, \bar{z})$ are massless scalar fields governed by a scale-dependent metric

$$T^{-1} g_{ij}(\Lambda) = (\Lambda\mu^{-1})^{2\gamma(i)}\, T^{-1} g_{ij}$$

At $|z_1 - z_2| \approx \Lambda^{-1}$, the insertions of the irrelevant $\phi_i(z, \bar{z})$ are suppressed by $(\mu\Lambda^{-1})^{\gamma(i)}$.

The irrelevant λ^i are not needed to fluctuate.

Finitely many $\lambda^i(z, \bar{z})$ fluctuate at every Λ^{-1}.

Change variables to the running coupling constants $\lambda^i_r = (\Lambda/\mu)^{\gamma(i)} \lambda^i$.

$$\left\langle\, \lambda^i_r(z_1, \bar{z}_1)\ \lambda^j_r(z_2, \bar{z}_2)\, \right\rangle \approx -T\, g^{ij}\ \ln(\Lambda^2\, |z_1 - z_2|^2)$$

governed by the scale invariant metric $T^{-1} g_{ij}$.

The lambda model

The gaussian fluctuations, patched together over the manifold of spacetimes, determine a nonlinear model. The interactions account for collisions of local handles. Recall $T \propto g_s^2$.

The λ-model is the nonlinear model

$$\int \mathrm{D}\lambda_r \, \mathrm{e}^{-S(\lambda_r)} \, \mathrm{e}^{-\int \mathrm{d}^2 z \, \Lambda^2 \frac{1}{2\pi} \lambda_r^i(z,\bar{z}) \, \phi_i^\Lambda(z,\bar{z})}$$

$$S(\lambda_r) = \int \mathrm{d}^2 z \, \frac{1}{2\pi} T^{-1} g_{ij}(\lambda_r) \, \partial\lambda_r^i \, \bar{\partial}\lambda_r^j$$

It has the same form at every 2d distance Λ^{-1}.

It is scale invariant in the generalized sense, unchanged under scaling

$$\Lambda^{-1} \to (1+\epsilon) \, \Lambda^{-1}$$

when combined with transforming the target manifold by the rg flow

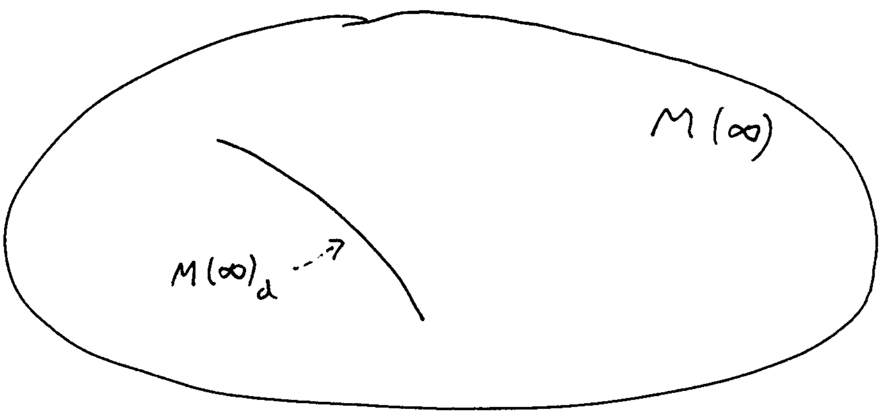
$$\lambda_r^i \to \lambda_r^i - \epsilon \, \beta^i(\lambda_r)$$

which is only a change of variables in the functional integral defining the model.

The λ-model has target manifold $M(L)$.

$M(L)$ is the manifold of spacetimes, the finite dimensional manifold of general N-L models. $M(L)$ depends on Λ^{-1} through $\mu/\Lambda = \mathrm{e}^{-L^2}$.

$M(L)$ is parametrized by the wave modes λ^i at spacetime distances $> L$. The λ^i at spacetime distances smaller than L are irrelevant, *decoupled*. L is a strong UV cutoff distance.



$M(\infty)$ is the manifold of fixed points $\beta = 0$.

$M(\infty)_d$ is the decompactification locus, where some dimensions become macroscopic, where $\gamma(i) \approx 0$ occur.

$M(L)$ is a “thickening” of $M(\infty)$ near $M(\infty)_d$.

The *a priori* measure on $M(L)$

The *a priori* measure is the distribution of fluctuations at 2d distances up to Λ^{-1}

$$\langle f \rangle = \langle f(\lambda_r(z,\bar{z})) \rangle = \int_{M(L)} f(\lambda_r)\, \mathrm{d}\rho_r(\Lambda, \lambda_r)$$

It diffuses in "time" $\ln(\Lambda^{-1})$

$$-\Lambda \frac{\partial}{\partial \Lambda} \mathrm{d}\rho_r = \nabla_i \left[T\, g^{ij}(\lambda_r) \nabla_j + \beta^i(\lambda_r) \right] \mathrm{d}\rho_r$$

Use the gradient property

$$\beta^i(\lambda_r) = T\, g^{ij}\, \partial_j \left(T^{-1} a(\lambda_r) \right)$$

to find the equilibrium measure

$$0 = \left[T\, g^{ij} \nabla_j + \beta^i \right] \mathrm{d}\rho_r$$

$$\mathrm{d}\rho_r = \mathrm{e}^{-T^{-1} a(\lambda_r)}\, \mathrm{dvol}(\lambda_r)$$

A measure on the spacetime wave modes.

The *a priori* measure is a spacetime quantum field theory with equation of motion $\beta = 0$,

It describes the large distance physics.

The expectation values in the *a priori* measure

$$\left\langle \lambda_r^{i_1} \lambda_r^{i_2} \cdots \right\rangle \qquad i = (p, \cdots)$$

are the correlation functions of the spacetime quantum field theory,

$$\left\langle \lambda_r^{i_1} \lambda_r^{i_2} \cdots \right\rangle \delta_{i_1} h_{\mu_1 \nu_2}(x_1)\, \delta_{i_2} h_{\mu_2 \nu_2}(x_2) \cdots$$

For example, at tree level,

$$\begin{aligned} \left\langle \lambda_r^i \, \lambda_r^j \right\rangle &= T\, g^{ij} \left[\frac{1 - (\Lambda\, |z_1 - z_2|)^{2\gamma(i)}}{\gamma(i)} \right]_{/z_1 = z_2} \\ &= T\, g^{ij} \, \frac{1}{\gamma(i)} \end{aligned}$$

which is the tree level propagator in spacetime.

Diffusion of the *a priori* measure to equilibrium

$\Rightarrow$ background independence
(diffusion forgets initial condition)

$\Rightarrow$ spacetime locality
(integrating out small distance wave modes undoes diffusion in those directions)

What the cancelling does

The λ fluctuations nonperturbatively produce the effective background spacetime Back(L), starting at $\Lambda_0^{-1} \approx 0$, $L_0 \approx \infty$.

2d distance	spacetime distance	
$< \Lambda^{-1}$	$> L$	λ-model, no handles
$> \Lambda^{-1}$	$< L$	handles in Back(L)

$\Lambda^{-1} \to (1+\epsilon)\Lambda^{-1}$, $L \to L - \epsilon$,

$$\text{Back}(L) + (\lambda \text{ fluctuations}) = \text{Back}(L-\epsilon)$$

The cancelling:

$$(\lambda \text{ fluctuations}) + (\text{handles}) = 0$$

So handles *undo* what the λ-model did:

$$\text{Back}(L) = \text{Back}(L-\epsilon) + (\text{handles})$$

Nonperturbative string theory (if it existed) would go from smaller to larger L, *undoing* the λ-model's construction of the effective background spacetime.

Unreliability of $\beta = 0$ string backgrounds

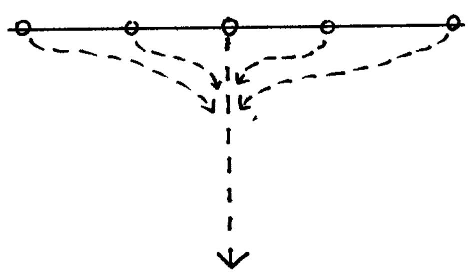
In the idealized pure S-matrix string theory:

1. start at $\Lambda^{-1} = 0$, $L = \infty$
2. find the manifold $M(\infty)$ of conventional $\beta = 0$ string backgrounds
3. extrapolate nonperturbative backgrounds assuming properties of the $\beta = 0$ backgrounds to hold nonperturbatively, notably spacetime supersymmetry.

In the realist λ-model:

1. start in $M(L_0)$ at $\Lambda_0^{-1} \approx 0$, $L_0 \approx \infty$
2. λ fluctuations act to Λ^{-1}, nonperturbatively producing the effective background at L
3. the limit $L \to \infty$ is to be investigated.

$\Lambda_0^{-1} \approx 0$, $L_0 \approx \infty$ $M(L_0)$



λ fluctuations

$\Lambda^{-1} > 0$, $L < \infty$ Back(L), $\mathrm{d}\rho_r(\Lambda, \lambda_r)$

Need $L^2 = \ln(\Lambda/\mu)$ large enough to be effectively a divergence, so renormalization of the general N-L model is valid.

$L^2 > 10^{24}$ or 10^{20} should be large enough.

L can be taken smaller than the smallest observable distance (assuming that the unit of distance is within a few orders of magnitude of the Planck length).

If the theory is right, the *a priori* measure is a quantum field theory describing all observable physics.

Can dispense with string theory, for practical purposes.

String theory is used only as an auxiliary technical apparatus, formally representing small distance physics.

λ-instantons

The λ-model is a nonperturbative two dimensional quantum field theory. Novel nonperturbative effects are expected at large distances in spacetime.

λ-instantons are the local minima of $S(\lambda_r)$, the harmonic surfaces $\lambda_H(z, \bar{z})$ in $M(L)$:

$$0 = \partial \left(T^{-1} g_{ij}(\lambda_H) \, \bar{\partial} \, \lambda_H^j \right)$$

Global: harmonic surfaces in $M(\infty)$. (Example given in paper.) Condense at macroscopic spacetimes?

Localized: harmonic surfaces in the manifold of spacetime fields in a macroscopic spacetime.

- nonperturbative e^{-S} corrections to $\beta^i(\lambda)$
- $S(\lambda_H) \propto g_s^{-2}$ (≈ 100 ?)
- produce small nonzero masses?
- remove spacetime supersymmetry?

Nontrivial π_2 homotopy classes do exist.
Hope for numbers $e^{-S(\lambda_H)}$ like $m_W^2 = e^{-78}$.

Tasks

The λ-model is a new (speculative) way to do spacetime physics. There is a lot to explore.

Immediate task: find out if nonperturbative effects can give small nonzero masses and remove spacetime supersymmetry.

Temporarily: assume a specific heterotic background spacetime with 4 macroscopic dimensions.

1. Find the harmonic surfaces in the manifold of 4d spacetime fields. Calculate $\mathrm{e}^{-S(\lambda_H)}$.

2. Derive formulas for mass corrections and supersymmetry violation.

3. Figure out how to calculate the 1-loop normalizing constant

$$\det{}^{-1/2}(-\nabla\bar{\partial})\ \ \mathrm{e}^{-\int \mathrm{d}^2 z\, \Lambda^2 \frac{1}{2\pi}\, \lambda_H^i(z,\bar{z})\, \phi_i^{\Lambda}(z,\bar{z})}$$