

Master

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Chapter 1

Introduction

1.1 Units

In this thesis, we employ *natural units*, defined by

$$\hbar = c = k_B = 1, \quad (1.1)$$

where \hbar is Planck's reduced constant, c is the speed of light, and k_B is Boltzmann's constant. Dimensionfull results are often given in MeV. To obtain results in the SI-system, we use the following conversion factors, as given by [1]

$$c = 2.998 \cdot 10^8 \text{ m s}^{-1}, \quad (1.2)$$

$$\hbar = 1.055 \cdot 10^{-34} \text{ J s}, \quad (1.3)$$

$$k_B = 1.380 \cdot 10^{-23} \text{ J K}^{-1}, \quad (1.4)$$

$$G = 6.674 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}, \quad (1.5)$$

where G is Newton's gravitational constant. The conversion factor between MeV and SI-units is

$$1 \text{ MeV} = 1.60218 \cdot 10^{-19} \text{ J}. \quad (1.6)$$

In the calculation in section 4.3, the value for the neutron mass is [1]

$$m_N = 939.57 \text{ MeV} = 1.674 \cdot 10^{-27} \text{ kg}. \quad (1.7)$$

In astronomical calculation, the solar mass is used, which is

$$M_{\odot} = 1.988 \cdot 10^{30} \text{ kg}. \quad (1.8)$$

1.2 Structure of thesis

To make this thesis as self contained as possible, we have included some parts from the earlier specialization project, with minor modifications. These sections are marked with an asteriks in the table of content.

citation

Chapter 2

Mathematics

General relativity describes how matter and energy curve the fabric of space and time. Einstein first wrote down the theory more than a century ago, and it is still our most accurate theory of gravitational effects. It makes accurate and counterintuitive predictions, which experiments have borne out. This chapter surveys the basics of general relativity and some mathematical prerequisites. We will then use this to derive the Tolman-Oppenheimer-Volkoff (TOV) equation, a differential equation used to model stars. This chapter is based on [2, 3].

2.1 Differential geometry

2.1.1 Manifolds and coordinates

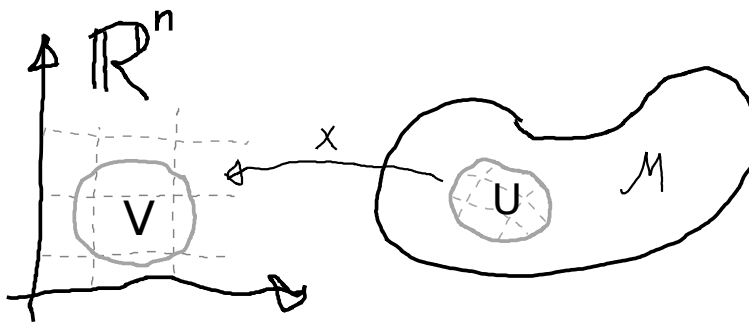


Figure 2.1: (Kladd) The coordinate function x maps a neighborhood U in the manifold \mathcal{M} to a neighborhood V in \mathbb{R}^n .

General relativity is formulated in the language of *differential geometry*, which generalizes multivariable calculus to more general spaces than \mathbb{R}^n . These spaces are *smooth manifolds*. An n -dimensional manifold, \mathcal{M} , is a set of points, locally homeomorphic to \mathbb{R}^n . That is, for all points $p \in \mathcal{M}$, there exists a neighborhood U around p , together with a corresponding set of continuous, bijective functions,

$$x : U \subseteq \mathcal{M} \mapsto V \subseteq \mathbb{R}^n, \quad (2.1)$$

$$p \mapsto x^\mu(p). \quad (2.2)$$

We call $x(p) = (x^0(p), \dots, x^{n-1}(p)) = x^\mu(p)$ a coordinate function of \mathcal{M} . The inverse of x , x^{-1} , obeys $x^{-1}(x(p)) = p$, for all $p \in U$. A smooth manifold is one in which the coordinate functions are infinitely differentiable. To define differentiability on manifolds, consider two coordinate functions, x , and x' . The corresponding domains U and U' may or may not overlap. We then define the transition function, a function



Figure 2.2: (Kladd) The transition map $f_{x' \rightarrow x}$ between two coordinate functions, x and x' , maps between the images of these function, via the manifold \mathcal{M} . The function's domain and image are restricted to a (possibly empty) subset of the images of x and x' . This is illustrated by the shaded regions in V and V' .

between subsets of \mathbb{R}^n by mapping via \mathcal{M} , as

$$f_{x \rightarrow x'} = x' \circ x^{-1} : \mathbb{R}^n \mapsto \mathbb{R}^n. \quad (2.3)$$

The map is illustrated in Figure 2.2.¹ A set of coordinate functions $\mathcal{A} = \{x_i\}$ whose domain cover \mathcal{M} is called an *atlas* of \mathcal{M} . If the transition function between all pairings of coordinate functions in the atlas is smooth—that is, infinitely differentiable—we call the atlas smooth. We then define a smooth manifold as the topological manifold \mathcal{M} together with a *maximal* smooth atlas \mathcal{A} . A smooth atlas is maximal if no coordinate function can be added while the atlas remains smooth.²

Consider two m - and n -dimensional smooth manifolds \mathcal{M} and \mathcal{N} . Let x denote the coordinates on \mathcal{M} , while y denotes the coordinates on \mathcal{N} . We can define smooth functions between these manifolds similarly to how we define smooth coordinates. Consider the function

$$F : \mathcal{M} \mapsto \mathcal{N}. \quad (2.4)$$

It is said to be smooth if, for all points $p \in \mathcal{M}$, there is a set of local coordinates x around p and y around $F(p)$ such that the map $\tilde{F} = y \circ F \circ x^{-1}$ is smooth. This map may be illustrated by a diagram,

$$\begin{array}{ccc} \mathcal{M} & \xrightarrow{F} & \mathcal{N} \\ \downarrow x & & \downarrow y \\ \mathbb{R}^m & \xrightarrow{\tilde{F}} & \mathbb{R}^n \end{array} \quad (2.5)$$

We will not be careful with the distinction between F , the function between the abstract manifolds, and \tilde{F} , the function of their coordinates, but rather denote both by $F(x)$. We may take the partial derivative of such a function with respect to the coordinates x , $\partial F / \partial x^\mu$. However, this is dependent on our choice of coordinates, as a set of local coordinates can always be scaled arbitrarily. Any physical theory must be independent of our choice of coordinates, so our next task is to define the properties of a smooth manifold in a coordinate independent way.

¹To be rigorous, one has to restrict the domains and image of the coordinate function when combining them. This is illustrated in Figure 2.2.

²The maximal condition ensures that two equivalent atlases correspond to the same differentiable manifold. A single manifold can be combined with different maximal atlases of smooth coordinates or differentiable structures. A set of examples are *exotic spheres*, smooth manifolds which are *homeomorphic* to S^n , but not *diffeomorphic*.

2.1.2 Vectors and tensors

A curve γ through \mathcal{M} is a function from \mathbb{R} to \mathcal{M} ,

$$\gamma : \mathbb{R} \mapsto \mathcal{M} \quad (2.6)$$

$$\lambda \mapsto \gamma(\lambda). \quad (2.7)$$

Such curves are often denoted only by their coordinates and the parameter λ , $x^\mu(\lambda) = (x^\mu \circ \gamma)(\lambda)$. With this curve, we can take the directional derivative of a real-valued function on the manifold, $f : \mathcal{M} \mapsto \mathbb{R}$. Assume $\gamma(\lambda = 0) = p$. As we are always taking the derivative of functions between \mathbb{R}^n , for different n , we can use the chain rule. The directional derivative of f at p , given by this curve γ , is then

$$\left. \frac{d}{d\lambda} f(x(\lambda)) \right|_p = \left. \frac{dx^\mu}{d\lambda} \right|_{\lambda=0} \left. \frac{\partial}{\partial x^\mu} f(x) \right|_p. \quad (2.8)$$

The set of all such directional derivatives, $d/d\lambda$ at p , form a vector space, $T_p\mathcal{M}$, called the *tangent space*. The tangent space is illustrated in Figure 2.3. The coordinates x^μ induce a basis of this vector space, namely partial derivatives with respect to the coordinate functions at p

$$e_\mu = \left. \frac{\partial}{\partial x^\mu} \right|_p = \partial_\mu|_p, \quad \mu \in \{0, \dots, n-1\}. \quad (2.9)$$

Any element $v \in T_p\mathcal{M}$ can therefore be written

$$v = v^\mu \partial_\mu|_p = \left. \frac{dx^\mu}{d\lambda} \right|_{\lambda=0} \left. \frac{\partial}{\partial x^\mu} \right|_p. \quad (2.10)$$

Here, λ is the parameter of the curve corresponding to the directional derivative v .³ The evaluation at $\lambda = 0$ and p will often be implicit for ease of notation. This directional derivative acts on functions $f : \mathcal{M} \mapsto \mathbb{R}$ as

$$v(f) = v^\mu \partial_\mu f. \quad (2.11)$$



Figure 2.3: (Kladd) The tangent space $T_p\mathcal{M}$, the shaded rectangle, is the set of all directional derivatives at $p \in \mathcal{M}$. A directional derivative is defined in terms of a curve that passes through p .

A map F between two manifolds \mathcal{M} and \mathcal{N} also induces a map between the tangent spaces of these manifolds. This is the *differential* of F at p ,

$$dF_p : T_p\mathcal{M} \mapsto T_p\mathcal{N}, \quad (2.12)$$

$$v \mapsto dF_p(v). \quad (2.13)$$

As $dF_p(v)$ is an element of $T_p\mathcal{N}$, directional derivative on \mathcal{N} , defined as

$$dF_p(v)(g) = v(g \circ F), \quad (2.14)$$

³There is not only one curve corresponding to any directional derivative but rather an equivalence class. We will gloss over this technicality, as it does not affect our work.

for functions $g : \mathcal{N} \mapsto \mathbb{R}$. It thus acts on functions on \mathcal{N} by “extending” the derivative v . This is a linear map between vector spaces and may be written in component form by considering the differentials of the coordinate functions. Denote the coordinates of \mathcal{N} by y^μ , and $y^\mu \circ F = F^\mu$. Then,

$$dF_p(\partial_\mu)(g) = \partial_\mu(g \circ F)|_p = \frac{\partial F^\nu}{\partial x^\mu} \bigg|_p \frac{\partial g}{\partial y^\nu} \bigg|_{F(p)}, \quad (2.15)$$

or more suggestively

$$dF \left(\frac{\partial}{\partial x^\mu} \right) = \frac{\partial F^\nu}{\partial x^\mu} \frac{\partial}{\partial y^\nu}. \quad (2.16)$$

This is a linear map of vectors between two vectors by the matrix $A_\mu{}^\nu = \partial_\mu F^\nu$. The differential is thus a generalization of the Jacobian. In the case of a real valued function, $f : \mathcal{M} \mapsto \mathbb{R}$, and $g : \mathbb{R} \mapsto \mathbb{R}$, we get

$$df(v)(g) = v(g \circ f) = (v^\mu \partial_\mu f) \frac{dg}{dy}. \quad (2.17)$$

df is thus a map from $T_p \mathcal{M}$ to $T_{f(p)} \mathbb{R}$, which is isomorphic to \mathbb{R} . The g be the identity function, so that $dg/dy = 1$. Then, the differential of a scalar function, also called a 1-form, is a map from vectors v to real numbers,

$$df(v) := v^\mu \partial_\mu f. \quad (2.18)$$

The set of all linear maps from a vector space V to the real numbers is called the *dual space* of V , denoted V^* . This is a new vector space with the same dimensionality as V . We denote the dual of $T_p \mathcal{M}$ as $T_p^* \mathcal{M}$. We can regard each coordinate function as a real-valued function with a corresponding differential. This differential obeys

$$dx^\mu(\partial_\nu) = \frac{\partial x^\mu}{\partial x^\nu} = \delta_\nu^\mu. \quad (2.19)$$

The differentials of the coordinate functions thus form a basis for $T_p^* \mathcal{M}$, called the dual basis. Any differential df can thus be written as $df = \omega_\mu dx^\mu$ for some components ω_μ . We find the components by applying the differential to the coordinate basis, $df(\partial_\mu) = \partial_\mu f = \omega_\mu$. In other words, we recover the classical expression

$$df = \frac{\partial f}{\partial x^\mu} dx^\mu, \quad (2.20)$$

however we now interpret it as a covector-field instead of an “infinitesimal displacement”.

Linear maps from vectors to real numbers is generalized by *tensors*. Given a vector space V , a general (n, m) tensor T is a multilinear map, which associates n elements from V and m from its dual V^* to the real numbers, i.e.,

$$T : V \times V \times \dots \times V^* \times \dots \mapsto \mathbb{R}, \quad (2.21)$$

$$(v, u, \dots; \omega, \dots) \mapsto T(v, u, \dots; \omega, \dots). \quad (2.22)$$

Multilinear means that T is linear in each argument. The set of all such maps is the tensor product space $V \otimes V \otimes \dots \otimes V^* \otimes \dots$, a $\dim(V)^{n+m}$ -dimensional vector space. If $\{e_\mu\}$ and $\{e^\mu\}$ are the basis for V and V^* , then we can write the basis of this of the tensor product space as $\{e_\mu \otimes \dots \otimes e^\nu \otimes \dots\}$. The tensor can thus be written

$$T = T^{\mu\nu\dots}{}_{\rho\dots} e_\mu \otimes e_\nu \otimes \dots e^\rho \otimes \dots, \quad (2.23)$$

where

$$T^{\mu\nu\dots}{}_{\rho\dots} = T(e^\mu e^\nu, \dots; e_\rho, \dots). \quad (2.24)$$

2.1.3 Geometries and the metric

The metric is a symmetric, non-degenerate $(0, 2)$ tensor

$$ds^2 = g_{\mu\nu} dx^\mu \otimes dx^\nu. \quad (2.25)$$

It defines the geometry of the manifold \mathcal{M} , and is the main object of study in general relativity. As it is invertible, we can define $g^{\mu\nu} = (g^{-1})_{\mu\nu}$, which is the components of a $(2,0)$ tensor. We use this to raise and lower indices, as is done with the Minkowski metric $\eta_{\mu\nu}$ in special relativity.

Up until now, we have only considered the tangent space $T_p\mathcal{M}$ at a point p and the corresponding tensor-product spaces. We are, however, more interested in *fields* of vectors, covectors, or tensors. For each point $p \in \mathcal{M}$, a tensor field T “picks out” a tensor $T(p)$ from each tensor product space corresponding to the tangent space at p , $T_p\mathcal{M}$. We will use a vector field to illustrate. This vector field can be written as

$$v(p) = v^\mu(p)\partial_\mu|_p. \quad (2.26)$$

We will mostly be working with the components v^μ , which are functions of \mathcal{M} . For ease of notation, we write the vector as a function of the coordinates x . The vector field $v(x)$ is unchanged by a coordinate-transformation $x^\mu \rightarrow x'^\mu$; the coordinates are only a tool for our convenience. However, with a new set of coordinates, we get a new set of basis vectors, ∂'_μ :

$$v = v^\mu \partial_\mu = v^\mu \frac{\partial x'^\nu}{\partial x^\mu} \partial'_\nu = v'^\mu \partial'_\mu, \quad (2.27)$$

This gives us the transformation rules for the components of vectors,

$$v'^\mu = \frac{\partial x'^\mu}{\partial x^\nu} v^\nu. \quad (2.28)$$

Tangent vectors are also called *contravariant* vectors, as their components transform contra to basis vectors. For covectors, it is

$$\omega'_\mu = \frac{\partial x^\nu}{\partial x'^\mu} \omega_\nu, \quad (2.29)$$

which is why covectors also are called *covariant* vectors.

The gradient of a scalar function f , $df = \partial_\mu f dx^\mu$, is a coordinate-independent derivative, as $\partial_\mu f$ follows the transformation law for covectors. We define the covariant derivative, ∇ , as a map from (n, m) tensor fields to $(n, m+1)$ tensor fields. When considering a scalar as a $(0,0)$ tensor, we see that this generalizes the scalar derivative. The components of a covariant derivative, $\nabla_\rho T^{\mu_1 \dots \mu_n}_{\nu_1 \dots \nu_m}$, must follow the tensor transformation law. However, this is not strong enough to uniquely define ∇ . We further assume

- Linearity: $\nabla(T + S) = \nabla T + \nabla S$.
- The product rule: $\nabla(T \otimes S) = (\nabla T) \otimes S + T \otimes (\nabla S)$.
- Reduces to partial derivative for scalars: $\nabla_\mu f = \partial_\mu f$.
- Kronecker delta gives zero: $\nabla_\mu \delta^\rho_\nu = 0$.

With this, we can, in general, write the covariant derivative as [2]

$$\nabla_\mu v^\nu = \partial_\mu v^\nu + \Gamma^\mu_{\nu\rho} v^\rho, \quad (2.30)$$

$$\nabla_\mu \omega_\nu = \partial_\mu \omega_\nu - \Gamma^\rho_{\mu\nu} \omega_\rho, \quad (2.31)$$

for vectors and covectors. $\Gamma^\mu_{\nu\rho}$ are called *Christoffel symbols*. The generalization for higher-order tensors is straightforward,

$$\nabla_\mu T^{\nu \dots \rho \dots} = \partial_\mu T^{\nu \dots \rho \dots} + \Gamma^\mu_{\nu\lambda} T^{\lambda \dots \rho \dots} + \dots - \Gamma^\lambda_{\mu\rho} T^{\mu \dots \lambda \dots} - \dots \quad (2.32)$$

This is still not enough to uniquely determine the covariant derivative. We will furthermore assume $\Gamma^\lambda_{\mu\nu} = \Gamma^\lambda_{\nu\mu}$ and $\nabla_\mu g_{\nu\rho} = 0$. With these, we can find an explicit formula of the Christoffel symbols in terms of the metric,

$$\Gamma^\rho_{\mu\nu} = \frac{1}{2} g^{\rho\sigma} (\partial_\mu g_{\nu\sigma} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu}). \quad (2.33)$$

The curvature of a manifold \mathcal{M} , with the metric $g_{\mu\nu}$, is encoded in the Riemann tensor. It is defined by

$$[\nabla_\mu, \nabla_\nu]v^\rho = R^\rho_{\sigma\mu\nu} v^\sigma, \quad (2.34)$$

which in our case gives the explicit formula

$$R^\rho{}_{\sigma\mu\nu} = \partial_\mu \Gamma^\rho_{\nu\sigma} - \partial_\nu \Gamma^\rho_{\mu\sigma} + \Gamma^\rho_{\mu\lambda} \Gamma^\lambda_{\nu\sigma} - \Gamma^\rho_{\nu\lambda} \Gamma^\lambda_{\mu\sigma}. \quad (2.35)$$

Although the Christoffel symbols are not tensors, the Riemann tensor is due to its definition using covariant derivatives. We can therefore contract some of its indices to get other tensor quantities. We define the Ricci tensor and Ricci scalar as

$$R_{\mu\nu} = R^\rho{}_{\mu\rho\nu}, \quad (2.36)$$

$$R = R^\mu{}_\mu = g^{\mu\nu} R_{\mu\nu}. \quad (2.37)$$

These are the quantities we need to start working with general relativity.

2.1.4 Integration on manifolds

The integral of a scalar function on a manifold is not a coordinate-independent notion, and we must introduce the notion of n -forms. A n -form is a antisymmetric $(0, n)$ tensor. To ease notation, we introduce the symmetrization of a tensor T ,

$$T_{(\mu_1 \dots \mu_n)} = \frac{1}{n!} \sum_{\sigma \in S_n} T_{\mu_{\sigma(1)} \dots \mu_{\sigma(n)}}, \quad (2.38)$$

where S_n is the set of all permutations of n objects. The antisymmetrization of a tensor is defined as

$$T_{[\mu_1 \dots \mu_n]} = \frac{1}{n!} \sum_{\sigma \in S_n} \text{sgn}(\sigma) T_{\mu_{\sigma(1)} \dots \mu_{\sigma(n)}}. \quad (2.39)$$

The function $\sigma = \pm 1$, depending on if σ is a even or odd permutation.

We are interested in a coordinated independent quantity that we can integrate over. To that end, we define

$$d^n x := dx^0 \wedge \dots \wedge dx^{n-1}. \quad (2.40)$$

Here, \wedge is the wedge product, defined as

$$(A \wedge B)_{\mu_1 \dots \mu_{n+m}} = \frac{(n+m)!}{n!m!} A_{[\mu_1 \dots \mu_n} B_{\mu_{n+1} \dots \mu_{n+m}]}, \quad (2.41)$$

Mer om wedge product

and dx^μ is the one-form corresponding to the x^μ -coordinate function. Given a different set of coordinates, x'^μ , these are related by

$$d^n x = \det \left(\frac{\partial x}{\partial x'} \right) d^n x', \quad (2.42)$$

Forklar

by the properties of the wedge product. We define $|g| = |\det(g_{\mu\nu})|$, which, by the transformation properties of tensors, transforms as

$$\sqrt{|g'|} = \left| \det \left(\frac{\partial x'}{\partial x} \right) \right| \sqrt{|g|}, \quad (2.43)$$

This means that we can use this to compensate for the transformation of $d^n x$, and get a volume form with a coordinate independent expression,

$$dV = \sqrt{|g|} d^n x = \sqrt{|g'|} d^n x'. \quad (2.44)$$

With this, we can integrate scalars in a well-defined way by mapping them to a corresponding n -form, $f \rightarrow f dV$. We define the integral of a scalar function f on a manifold \mathcal{M} with a metric g as

$$I = \int_{\mathcal{M}} dV f = \int_{\mathcal{M}} d^n x \sqrt{|g(x)|} f(x). \quad (2.45)$$

Stoke's theorem generalizes the fundamental theorem of calculus and the divergence theorem to manifolds. The most general statement of the theorem uses the exterior derivative, a map from n -forms to $n+1$ -forms, defined by

Skriv mer om hva dette er

$$(\mathrm{d}T)_{\mu_1 \dots \mu_{n+1}} = (n+1) \partial_{[\mu_1} T_{\mu_2 \dots \mu_{n+1}]} \quad (2.46)$$

Let \mathcal{M} be a differential manifold of dimension n , with the boundary $\partial\mathcal{M}$. Stoke's theorem says that, for an $n-1$ -form ω ,

$$\int_{\mathcal{M}} \mathrm{d}\omega = \int_{\partial\mathcal{M}} \omega. \quad (2.47)$$

Stoke's theorem then implies a generalized divergence theorem. The boundary of \mathcal{M} is a $n-1$ manifold dimensional, and a metric g on \mathcal{M} will induce a new metric γ on $\partial\mathcal{M}$. This metric corresponds to the restriction of g to $\partial\mathcal{M}$. Furthermore, there will be a vector field n^μ of normalized vectors orthogonal to all elements of $T\partial\mathcal{M}$. This theorem states that for a vector field V^μ on \mathcal{M} ,

$$\int_{\mathcal{M}} \mathrm{d}^n x \sqrt{|g|} \nabla_\mu V^\mu = \int_{\partial\mathcal{M}} \mathrm{d}^{n-1} y \sqrt{|\gamma|} n_\mu V^\mu. \quad (2.48)$$

2.2 Lie groups

This section is adapted from (PROSJEKTOPPGAVE).

Make this section fit better into this thesis

Lie groups are a natural structure to capture the symmetries of a theory. A Lie group is a smooth manifold, i.e., a space that is locally diffeomorphic to \mathbb{R}^N . This means that we can locally parametrize the space by N real numbers η_α , using smooth invertible functions. A Lie group is also equipped with group structure. A group is a set, G , together with a map

$$(\cdot, \cdot) : G \times G \mapsto G, \quad (2.49)$$

$$(g_1, g_2) \mapsto g_3, \quad (2.50)$$

called group multiplication. This map obeys the group axioms, which are the existence of an identity element $\mathbb{1}$, associativity and the existence of an inverse element g^{-1} for all $g \in G$. These can be written as

$$\begin{aligned} \forall g \in G, & \quad (g, \mathbb{1}) = g, \\ \forall g_1, g_2, g_3 \in G, & \quad (g_1, (g_2, g_3)) = ((g_1, g_2), g_3), \\ \forall g \in G, \exists g^{-1} \in G, \text{ s.t., } & \quad (g, g^{-1}) = \mathbb{1}. \end{aligned}$$

In addition, we require that both the multiplication map and the inverse map, $g \mapsto g^{-1}$, are smooth. We describe the set of continuous symmetry transformations,

$$G = \{ g \mid g\varphi = \varphi', S[\varphi'] = S[\varphi], \mathcal{D}\varphi' = \mathcal{D}\varphi \}, \quad (2.51)$$

as a Lie group. The group G might act on φ linearly, so $(g\varphi)_i = g_{ij}\varphi_j$, or in a more complicated matter. In this case, the group multiplication is composition, i.e., performing transformations in succession. This map is closed, as the composite of two symmetry transformations is another symmetry transformation. The identity map is a symmetry transformation, and composition is associative. This means that invertible symmetry transformations form a group.

We will focus on connected Lie groups, in which all elements $g \in G$ are in the same connected piece as the identity map $\mathbb{1}\varphi = \varphi$. This means that for each $g \in G$, one can find a continuous path $\gamma(t)$ in the manifold, such that $\gamma(0) = \mathbb{1}$ and $\gamma(1) = g$. Given such a path, we can study transformations close to the identity element. As the Lie group is a smooth manifold, we can write⁴

$$\gamma(\epsilon) = \mathbb{1} + i\epsilon V + \mathcal{O}\epsilon. \quad (2.52)$$

V is a generator, and is defined as

$$iV = \left. \frac{\mathrm{d}\gamma}{\mathrm{d}t} \right|_{t=0}. \quad (2.53)$$

⁴The factor i is a physics convention and differs from how mathematicians define generators of a Lie group.

We can define a path γ in G by its path through parameter space \mathbb{R}^n , $\gamma(t) = g(\eta(t))$. Here, $\eta_\alpha(t)$ is a path through \mathbb{R}^N , the coordinates of G , such that $\eta_\alpha(0) = 0$ and $g(0) = \mathbb{1}$. We can thus write the generator as

$$V = \left. \frac{d\gamma}{dt} \right|_{t=0} = \left. \frac{d\eta_\alpha}{dt} \right|_{t=0} \left. \frac{\partial g}{\partial \eta_\alpha} \right|_{\eta=0} = v_\alpha T_\alpha, \quad T_\alpha = \left. \frac{d\eta_\alpha}{dt} \right|_{t=0}, \quad \left. \frac{\partial g}{\partial \eta_\alpha} \right|_{\eta=0}. \quad (2.54)$$

One can show that the generators form a vector space, with the basis T_α , induced by the coordinates η_α [3]. This vector space is called the tangent space of the identity element, $T_1 G$. Infinitesimal transformations can therefore be written as

$$\gamma(\epsilon) = \mathbb{1} + i\epsilon v_\alpha T_\alpha + \mathcal{O}(\epsilon). \quad (2.55)$$

The tangent space, together with the additional operation

$$[T_\alpha, T_\beta] = iC_{\alpha\beta}^\gamma T_\gamma, \quad (2.56)$$

called the Lie bracket, form a Lie algebra denoted \mathfrak{g} . $C_{\alpha\beta}^\gamma$ are called structure constants. They obey the Jacobi identity,

$$C_{\alpha\beta}^\gamma + C_{\beta\gamma}^\alpha + C_{\gamma\alpha}^\beta = 0, \quad (2.57)$$

which mean that they are totally antisymmetric. For matrix groups, which we deal with in this text, the Lie bracket is the commutator. A subset of the original Lie group, $H \subset G$, closed under the group action, is called a subgroup. H then has its own Lie algebra \mathfrak{h} , with a set of $m = \dim H$ generators, t_a , which is a subset of the original generators T_α . We denote the remaining set of generators x_i , such that t_a and x_i together span \mathfrak{g} . The commutators of t_a must be closed, which means that we can write

$$[t_a, t_b] = iC_{ab}^c t_c, \quad (2.58)$$

$$[t_a, x_i] = iC_{ai}^k x_k, \quad (2.59)$$

$$[x_i, x_j] = iC_{ij}^k x_k + iC_{ij}^c t_c, \quad (2.60)$$

where abc runs over the generators of \mathfrak{h} , and ijk runs over the rest. The second formula can be derived using the Jacobi identity REF:jacobi identity, which implies that $C_{ab}^k = 0 = -C_{ak}^b$. This is called a Cartan decomposition.

One parameter subgroups are one special case of Lie subgroups. If a curve $\gamma(t)$ through G obey

$$\gamma(t)\gamma(s) = \gamma(t+s), \quad \gamma(0) = \mathbb{1}, \quad (2.61)$$

then all the points on this curve form a one parameter subgroup of G . This path is associated with a generator,

$$\left. \frac{d\gamma}{dt} \right|_{t=0} = i\eta_\alpha T_\alpha. \quad (2.62)$$

This association is one-to-one, and allows us to define the exponential map,

$$\exp\{i\eta_\alpha T_\alpha\} := \gamma(1). \quad (2.63)$$

For connected and compact Lie groups, all elements of the Lie group $g \in G$ can be written as an exponential of elements in the corresponding Lie algebra $\eta_\alpha T_\alpha \in \mathfrak{g}$. For matrix groups, the exponential equals the familiar series expansion [3]

$$\exp\{X\} = \sum_n \frac{1}{n!} X^n. \quad (2.64)$$

Chapter 3

Quantum field theory and the equation of state

In this section, we survey some general properties of quantum field theory that are necessary for chiral perturbation theory. First, we introduce the path integral and the 1-particle irreducible effective action and the effective potential. We will derive Goldstone's theorem and present the CCWZ construction, which are the basis for χ PT.

3.1 QFT via path integrals

This section is based on [4–7]

In the path integral formalism, one evaluates quantum observable by integrating over the contributions of all possible configurations. If the system has specified initial and final states, this amounts to all possible paths the system might evolve between these, hence the name. We assume the reader has some familiarity with this formalism. However, if a refresher is needed (Ref: imaginary time formalism) [contains a derivation of the closely related imaginary-time formalism and compares it with the path integral approach.](#)

Ha imag-time
appendix

In the path integral formalism, the vacuum-to-vacuum transition amplitude, i.e., the probability that that vacuum at $t = -\infty$ evolves to the vacuum at time $t = \infty$, is given by

Write better

$$Z = \lim_{T \rightarrow \infty} \langle \Omega, T/2 | -T/2, \Omega \rangle = \lim_{T \rightarrow \infty} \langle \Omega | e^{-iHT} | \Omega \rangle = \int \mathcal{D}\pi \mathcal{D}\varphi \exp \left\{ i \int d^4x (\pi \dot{\varphi} - \mathcal{H}[\pi, \varphi]) \right\}, \quad (3.1)$$

where $|\Omega\rangle$ is the vacuum state. The φ are the fields of the theory, and π their canonical momenta. We will work as if φ are a bosonic field. However, this can be readily generalized to fermions. By introducing a source term into the Hamiltonian density, $\mathcal{H} \rightarrow \mathcal{H} - J(x)\varphi(x)$, we get the generating functional

$$Z[J] = \int \mathcal{D}\pi \mathcal{D}\varphi \exp \left\{ i \int d^4x (\pi \dot{\varphi} - \mathcal{H}[\pi, \varphi] + J\varphi) \right\}. \quad (3.2)$$

If \mathcal{H} is quadratic in π , we can complete the square and integrate out π to obtain

$$Z[J] = C \int \mathcal{D}\varphi \exp \left\{ i \int d^4x (\mathcal{L}[\varphi] + J\varphi) \right\}. \quad (3.3)$$

C is infinite, but constant, and will drop out of physical quantities. In scattering theory, the main objects of study are correlation functions $\langle \varphi(x_1)\varphi(x_2)\dots \rangle = \langle \Omega | T \{ \varphi(x_1)\varphi(x_2)\dots \} | \Omega \rangle$, where T is the time ordering operator. These are given by functional derivatives of $Z[J]$,

$$\langle \varphi(x_1)\varphi(x_2)\dots \rangle = \frac{\int \mathcal{D}\varphi(x) [\varphi(x_1)\varphi(x_2)\dots] e^{iS[\varphi]}}{\int \mathcal{D}\varphi(x) e^{iS[\varphi]}} = \frac{1}{Z[0]} \prod_i \left(-i \frac{\delta}{\delta J(x_i)} \right) Z[J] \Big|_{J=0}, \quad (3.4)$$

where

$$S[\varphi] = \int d^4x \mathcal{L}[\varphi] \quad (3.5)$$

is the action of the theory. The functional derivative is described in section A.1. In a free theory, we are able to write

$$Z_0[J] = Z_0[0] \exp(iW_0[J]), \quad iW_0[J] = -\frac{1}{2} \int d^4x d^4y J(x) D_0(x-y) J(y), \quad (3.6)$$

where D_0 is the propagator of the free theory. Using this form of the generating functional, () becomes

$$\begin{aligned} \frac{1}{Z[0]} (-i)^n \frac{\delta}{\delta J(x_1)} \cdots \frac{\delta}{\delta J(x_n)} Z_0[J] \Big|_{J=0} &= (-i)^n \frac{\delta}{\delta J(x_1)} \cdots \frac{\delta}{\delta J(x_n)} e^{iW_0[J]} \Big|_{J=0} \\ &= (-i)^n \frac{\delta}{\delta J(x_1)} \cdots \frac{\delta}{\delta J(x_{n-1})} \left(i \frac{\delta W_0[J]}{\delta J(x_n)} \right) e^{iW_0[J]} \Big|_{J=0} \\ &= (-i)^n \frac{\delta}{\delta J(x_1)} \cdots \frac{\delta}{\delta J(x_{n-2})} \left(i \frac{\delta W_0[J]}{\delta J(x_{n-1}), J(x_n)} + i^2 \frac{\delta W_0[J]}{\delta J(x_{n-1})} \frac{\delta W_0[J]}{\delta J(x_n)} \right) e^{iW_0[J]} \Big|_{J=0} = \dots \\ &= (-i)^{\lfloor n/2 \rfloor} \sum_{(a,b)} \prod_{i=1}^{\lfloor n/2 \rfloor} \frac{\delta W_0[J]}{\delta J(x_{a(i)}, J(x_{b(i)}))} \Big|_{J=0}. \end{aligned}$$

In the last line we have introduced the functions a, b , which define a way to pair up n elements. $\lfloor \cdot \rfloor$ is the floor function. The domain of these functions are the integers between 1 and $\lfloor n/2 \rfloor$, the image a subset of the integers between 1 and n of size $\lfloor n/2 \rfloor$. A valid pairing is a set $\{(a(1), b(1)), \dots, (a(\lfloor n/2 \rfloor), b(\lfloor n/2 \rfloor))\}$, where all elements $a(i)$ and $b(j)$ are different, such that all integers up to and including n are featured. A pair is not directed, so $(a(i), b(i))$ is the same pair as $(b(i), a(i))$. The sum is over the set $\{(a, b)\}$ of all possible, unique pairings. If n is odd, the expression is equal to 0. This is Wick's theorem, and it can more simply be stated as *a correlation function is the sum of all possible pairings of 2-point functions*,

$$\left\langle \prod_{i=1}^n \varphi(x_i) \right\rangle_0 = \sum_{\{(a,b)\}} \prod_{i=1}^{\lfloor n/2 \rfloor} \langle \varphi(x_{a(i)}) \varphi(x_{b(i)}) \rangle_0. \quad (3.7)$$

The subscript on the expectation value indicates that it is evaluated in the free theory.

If we have an interacting theory, that is, a theory with an action $S = S_0 + S_I$, where S_0 is a free theory, the generating functional can be written

$$Z[J] = Z_0[0] \left\langle \exp \left(iS_I + i \int d^4x J(x) \varphi(x) \right) \right\rangle_0. \quad (3.8)$$

We can expand the exponential in power series, which means the expectation value in Eq. (3.8) becomes

$$\sum_{n,m} \frac{1}{n!m!} \left\langle (iS_I)^n \left(i \int d^4x J(x) \varphi(x) \right)^m \right\rangle_0. \quad (3.9)$$

The terms in this series are represented by Feynman diagrams, constructed using the Feynman rules, and can be read from the action. We will not further detail how the Feynman rules are derived. The Feynman rules for a free scalar field in thermal field theory are derived in (section:interacting scalar), and the general procedure is found in any of the main sources for this section [4–7] The source terms gives rise to an additional vertex The generating functional $Z[J]$ thus equals $Z_0[0]$ times the *sum of all diagrams with external sources* $J(x)$.

Consider a general diagram without external legs, built up of N different connected subdiagrams, where subdiagram i appears n_i times. As an illustration, a generic vacuum diagram in φ^4 -theory has the form

$$\mathcal{M} = \quad (3.10)$$

If sub-diagram i as a stand-alone diagram equals \mathcal{M}_i , each copy of that subdiagram contributes a factor \mathcal{M}_i to the total diagram. However, due to the symmetry of permuting identical subdiagrams, one must divide

by the extra symmetry factor $s = n_i!$, the total number of permutations of all the copies of diagram i . The full diagram therefore equals

$$\mathcal{M} = \prod_{i=1}^N \frac{1}{n_i!} \mathcal{M}_i^{n_i}. \quad (3.11)$$

\mathcal{M} is uniquely defined by a finite sequence of integers, $(n_1, n_2, \dots, n_N, 0, 0, \dots)$, so the sum of all diagrams is the sum over the set S of all finite sequences of integers. This allows us to write the sum of all diagrams as

$$\sum_{(n_1, \dots) \in S} \prod_i \frac{1}{n_i!} \mathcal{M}_i^{n_i} = \prod_{i=1}^{\infty} \sum_{n_i=1}^{\infty} \frac{1}{n_i!} \mathcal{M}_i^{n_i} = \exp\left(\sum_i \mathcal{M}_i\right). \quad (3.12)$$

We showed that the generating functional $Z[J]$ were the $Z_0[0]$ times the sum of all diagrams due to external sources. From Eq. (3.12), if we define

$$Z[J] = Z_0[0] \exp(iW[J]), \quad (3.13)$$

then $W[J]$ is the sum of all connected diagrams. This is trivially true for the free theory, where the only connected diagram is

$$W_0[J] = \quad (3.14)$$

Fix feynman-
diagrams

The two-point function in the full, interacting theory can thus be written

$$-i \frac{\delta W[J]}{\delta J(x), J(y)} = D(x - y). \quad (3.15)$$

3.2 The 1PI effective action

The generating functional for connected diagrams, $W[J]$, is dependent on the external source current J . We can define a new quantity with a different independent variable, using the Legendre transformation analogously to what is done in thermodynamics and Lagrangian mechanics. The new independent variable is

$$\varphi_J(x) := \frac{\delta W[J]}{\delta J(x)} = \langle \varphi(x) \rangle_J. \quad (3.16)$$

The subscript J on the expectation value indicate that it is evaluated in the presence of a source. The Legendre transformation of W is then

$$\Gamma[\varphi_J] = W[J] - \int d^4x J(x) \varphi_J(x). \quad (3.17)$$

Using the definition of φ_J , we have that

$$\frac{\delta \varphi_J(x)}{\delta \Gamma} [\varphi_J] = \int d^4y \frac{\delta J(y)}{\delta \varphi_J(x)} \frac{\delta J(y)}{\delta W} [J] - \int d^4y \frac{\delta J(y)}{\delta \varphi_J(x)} \varphi_J(y) - J(x) = -J(x). \quad (3.18)$$

If we compare this to the classical equations of motion of a field φ with the action S ,

$$\frac{\delta S[\varphi]}{\delta \varphi(x)} = -J(x), \quad (3.19)$$

we see that Γ is an action that gives the equation of motion for the expectation value of the field, given a source current $J(x)$.

To interpret Γ further, we observe what happens if we treat $\Gamma[\varphi]$ as a classical action with a coupling g . The generating functional in this new theory is

$$Z[J, g] = \int \mathcal{D}\varphi \exp\left\{ig^{-1} \left(\Gamma[\varphi] + \int d^4x \varphi(x) J(x) \right)\right\} \quad (3.20)$$

The free propagator in this theory will be proportional to g , as it is given by the inverse of the equation of motion for the free theory. All vertices in this theory, on the other hand, will be proportional to g^{-1} , as they are given by the higher-order terms in the action $g^{-1}\Gamma$. This means that a diagram with V vertices and I internal lines is proportional to g^{I-V} . Regardless of what the Feynman-diagrams in this theory are, the number of loops of a connected diagram is¹

$$L = I - V + 1. \quad (3.21)$$

To see this, we first observe that diagrams with one single loop must have equally many internal lines as vertices, so the formula holds for $L = 1$. The formula still holds if we add a new loop to a diagram with n loops by joining two vertices. If we attach a new vertex with one line, the formula still holds, and as the diagram is connected, any more lines connecting the new vertex to the diagram will create additional loops. This ensures that the formula holds by induction. As a consequence of this, any diagram is proportional to g^{L-1} . This means that in the limit $g \rightarrow 0$, the theory is fully described at the tree-level, i.e., by only considering diagrams without loops. In this limit, we may use the stationary phase approximation, as described in section A.1, which gives

$$Z[J, g \rightarrow 0] \approx C \det\left(-\frac{\delta\Gamma[\varphi_J]}{\delta\varphi(x), \varphi(y)}\right) \exp\left\{ig^{-1}\left(\Gamma[\varphi_J] + \int d^4x J(x)\varphi_J(x)\right)\right\}. \quad (3.22)$$

This means that

$$-ig \ln(Z[J, g]) = gW[J, g] = \Gamma[\varphi_J] + \int d^4x J(x)\varphi_J(x) + \mathcal{O}(g), \quad (3.23)$$

which is exactly the Legendre transformation we started out with, modulo the factor g . Γ is, therefore, the action that describes the full theory at the tree level. For a free theory, the classical action S equals the effective action.

As we found in the last section, the propagator $D(x, y) = \langle\varphi(x)\varphi(y)\rangle_J$ is given by $-i$ times the second functional derivative of $W[J]$. Using the chain rule, together with Eq. (3.18), we get

$$(-i) \int d^4z \frac{\delta^2 W[J]}{\delta J(x)\delta J(z)} \frac{\delta^2 \Gamma[\varphi_J]}{\delta\varphi_J(z)\delta\varphi_J(y)} = (-i) \int d^4z \frac{\delta\varphi_J[z]}{\delta J(x)} \frac{\delta^2 \Gamma[\varphi_J]}{\delta\varphi_J(z)\delta\varphi_J(y)} = \frac{\delta}{\delta J(x)} \frac{\delta\Gamma[\varphi_J]}{\delta\varphi_J(y)} = i\delta(x - y). \quad (3.24)$$

This is exactly the definition of the inverse propagator,

$$\frac{\delta\Gamma[\varphi_J]}{\delta\varphi_J(x), \varphi_J(y)} = D^{-1}(x, y). \quad (3.25)$$

The inverse propagator is the sum of all one-particle-irreducible (1PI) diagrams, with two external vertices. More generally, Γ is the generating functional for 1PI diagrams, which is why it is called the 1PI effective action.

Γ may be viewed as an effective action as defined in the introduction. We define η as the fluctuations around the expectation value of the field, $\varphi(x) = \varphi_J(x) + \eta(x)$, and use this to change variables of integration in the path integral. The expectation value φ_J is constant with respect to the integral, so

$$\int \mathcal{D}\varphi \exp\{iS[\varphi]\} = \int \mathcal{D}\eta \exp\{iS[\varphi_J + \eta]\}. \quad (3.26)$$

By assumption, $\langle\eta\rangle_J = 0$, which means this path integral is described by only 1PI diagrams, connected or not. We can therefore write

$$\exp\{i\Gamma[\varphi_J]\} = \int \mathcal{D}\eta \exp\{iS[\varphi_J + \eta]\}. \quad (3.27)$$

Comparing this to integrating out degrees of freedom, we see that the 1PI effective potential corresponds to integrating out *all* degrees of freedom, and let the expectation value appear as a static background field,

¹This is a consequence of the Euler characteristic $\chi = V - E + F$.

3.2.1 Effective potential

For a constant field configuration $\varphi(x) = \varphi_0$, the effective action, which is a functional, becomes a regular function. We define the effective potential \mathcal{V}_{eff} by

$$\Gamma[\varphi_0] = -VT \mathcal{V}_{\text{eff}}(\varphi_0), \quad (3.28)$$

where VT is the volume of space-time. For a constant ground state, the effective potential will equal the energy of this state. To calculate the effective potential, we can expand the action around this state to calculate the effective action, by changing variables to $\varphi(x) = \varphi_0 + \eta(x)$. $\eta(x)$ now parametrizes fluctuations around the ground state, and has by assumption a vanishing expectation value. The generating functional becomes

$$Z[J] = \int \mathcal{D}(\varphi_0 + \eta) \exp \left\{ iS[\varphi_0 + \eta] + i \int d^4x [\varphi_0 + \eta(x)] J(x) \right\}. \quad (3.29)$$

The functional version of a Taylor expansion, as described in section A.1, is

$$S[\varphi_0 + \eta] = S[\varphi_0] + \int dx \eta(x) \frac{\delta S[\varphi_0]}{\delta \varphi(x)} + \frac{1}{2} \int dx dy \eta(x) \eta(y) \frac{\delta^2 S[\varphi_0]}{\delta \varphi(x) \delta \varphi(y)} + \dots \quad (3.30)$$

The notation

$$\frac{\delta S[\varphi_0]}{\delta \varphi(x)} \quad (3.31)$$

indicates that the functional $S[\varphi]$ is differentiated with respect to $\varphi(x)$, then evaluated at $\varphi(x) = \varphi_0$. We define

$$S_0[\eta] := \int d^4x d^4y \eta(x) \eta(y) \frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y)}, \quad (3.32)$$

$$S_I[\eta] := \int d^4x d^4y d^4z \eta(x) \eta(y) \eta(z) \frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y), \varphi(z)} + \dots, \quad (3.33)$$

where the dots indicate higher derivatives. When we insert this expansion into the generating functional $Z[J]$ we get

$$Z[J] = \int \mathcal{D}\eta \exp \left\{ i \int d^4x (\mathcal{L}[\varphi_0] + J\varphi_0) + i \int d^4x \eta(x) \left(\frac{\delta S[\varphi_0]}{\delta \varphi(x)} + J(x) \right) + iS_0[\eta] + iS_I[\eta] \right\} \quad (3.34)$$

The first term is constant with respect to η and may be taken outside the path integral. The second term gives rise to tadpole diagrams, which alter the expectation value of $\eta(x)$. For $J = 0$, this expectation value should vanish, and this term can be ignored. Furthermore, this means that the ground state must minimize the classical potential,

$$\frac{\partial \mathcal{V}(\varphi_0)}{\partial \varphi} = 0. \quad (3.35)$$

This leaves us with

$$-i \ln Z[J] = W[J] = \int d^4x (\mathcal{L}[\varphi_0] + J\varphi_0) - i \ln \left(\int \mathcal{D}\eta \exp \{ iS_0[\eta] + iS_I[\eta] \} \right) \quad (3.36)$$

We can now use the definition of the 1PI effective action to obtain a formula for the effective potential,

$$\mathcal{V}_{\text{eff}}(\varphi_0) = -\frac{1}{VT} \left(W[J] - \int d^4x J(x) \varphi_0 \right) = \mathcal{V}(\varphi_0) - i \ln \left(\int \mathcal{D}\eta \exp \{ iS_0[\eta] + iS_I[\eta] \} \right). \quad (3.37)$$

In Eq. (3.17), we showed that the 1PI effective action describes the whole quantum theory of the original action at the tree-level. This was done by inspecting a theory with an action proportional to g^{-1} . In this theory, Feynman diagrams with L loops are proportional to g^{L-1} . We can use the same argument to expand the effective potential in loops. This is done by modifying the action $S[\varphi] \rightarrow g^{-1}S[\varphi]$, and then expand in

power of g . The first term in the effective potential is modified by $\mathcal{V} \rightarrow g^{-1}\mathcal{V}$, which means that it is made up of tree-level terms. This is as expected, since the tree-level result corresponds to the classical result without any quantum corrections. The second term becomes

$$\ln \left(\int \mathcal{D}\eta e^{iS_0 + iS_I} \right) \longrightarrow \ln \left(\int \mathcal{D}\eta e^{ig^{-1}S_0 + ig^{-1}S_I} \right) = \ln \left(\int \mathcal{D}\eta e^{ig^{-1}S_0} \right) + \ln \left(\frac{\int \mathcal{D}\eta e^{ig^{-1}S_I} e^{ig^{-1}S_0}}{\int \mathcal{D}\eta e^{ig^{-1}S_0}} \right)$$

The first term is quadratic in η , and can therefore be evaluated as a generalized Gaussian integral, as described in section A.1,

$$\begin{aligned} & \ln \left\{ \int \mathcal{D}\eta \exp \left(ig^{-1} \frac{1}{2} \int d^4x d^4y \eta(x) \eta(y) \frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y)} \right) \right\} \\ &= \ln \left\{ \det \left(-g^{-1} \frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y)} \right)^{-1/2} \right\} = -\frac{1}{2} \text{Tr} \left\{ \ln \left(-\frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y)} \right) \right\} + \text{const.} \end{aligned}$$

We then use the identity $\ln \det M = \text{Tr} \ln M$. After we remove the constant, this term is proportional to g^0 , i.e., it is made up of one-loop terms.

The last term can be evaluated by first expanding the exponential containing the S_I term, then using $\ln(1+x) = \sum_n \frac{1}{n} x^n$. Using

$$\langle A \rangle_0 = \frac{\int \mathcal{D}\varphi A e^{ig^{-1}S_0}}{\int \mathcal{D}\varphi e^{ig^{-1}S_0}}, \quad (3.38)$$

we can write

$$\ln \left[\frac{\int \mathcal{D}\eta e^{ig^{-1}S_I} e^{ig^{-1}S_0}}{\int \mathcal{D}\varphi e^{ig^{-1}S_0}} \right] = \ln \left(\sum_{n=0}^{\infty} \frac{1}{n!} \langle (ig^{-1}S_I)^n \rangle_0 \right). \quad (3.39)$$

We recognize this as the sum of all connected Feynman diagrams, with Feynman rules from the interaction term S_I . We know that S_I is made up of terms that are third power or higher in the fields. Each internal line is connected to two vertices, and each vertex is connected to at least three internal lines, i.e., $I \geq 3/2V$. The number of loops is therefore $L = I - V + 1 \geq (3/2 - 1)V + 1$. There is at least one vertex, i.e. $L \geq 3/2$. This shows that the first logarithm contains *all* one-loop contributions. The effective potential to one-loop order is therefore

$$\mathcal{V}_{\text{eff}}(\varphi_0) = \mathcal{V}(\varphi_0) - \frac{i}{VT} \frac{1}{2} \text{Tr} \left\{ \ln \left(-\frac{\delta S[\varphi_0]}{\delta \varphi(x), \varphi(y)} \right) \right\}. \quad (3.40)$$

3.3 Symmetry and Goldstone's theorem

This section is based on [3–6].

Symmetry plays a prominent role in modern physics. If we can transform a physical state in such a way that the governing equations of this system are unchanged, we call that transformation a *symmetry transformation*. All such transformations are known as the symmetries of that theory. The symmetries of a theory encode a lot of physics, such as the presence of conserved quantities and the system's low energy behavior. We distinguish between internal and external symmetries. An external symmetry is an active coordinate transformation, such as rotations or translations. They relate degrees of freedom at different space-time points, while internal symmetries transform degrees of freedom at each space-time point independently. A further distinction is between global and local symmetry transformations. Global transformations have one rule for transforming degrees of freedom at each point, which is applied everywhere, while local transformations are functions of space-time.

In classical field theory, symmetries are encoded in the behavior of the Lagrangian when the fields are transformed. We will consider continuous transformations, which can in general be written as

$$\varphi(x) \longrightarrow \varphi'(x) = f_t[\varphi](x), \quad t \in [0, 1]. \quad (3.41)$$

Here, $f_t[\varphi]$ is a functional in φ , and a smooth function of t , with the constraint that $f_0[\varphi] = \varphi$. This allows us to look at “infinitesimal” transformations,

$$\varphi'(x) = f_\epsilon[\varphi] = \varphi(x) + \epsilon \left. \frac{df_t[\varphi]}{dt} \right|_{t=0} + \mathcal{O}\epsilon. \quad (3.42)$$

When considering infinitesimal transformations, we will not always write $+\mathcal{O}\epsilon$, but rather consider it implicit. We will consider internal, global transformations which act linearly on φ . For N fields, φ_i , this can be written

$$\varphi'_i(x) = \varphi_i(x) + \epsilon iV_{ij}\varphi_j(x). \quad (3.43)$$

V_{ij} is called the generator of the transformation. A symmetry transformation of the system is then a transformation in which the Lagrangian left is unchanged, or at most differ by a 4-divergence term. That is, a transformation $\varphi \rightarrow \varphi'$ is a symmetry if

$$\mathcal{L}[\varphi'] = \mathcal{L}[\varphi] + \partial_\mu K^\mu[\varphi], \quad (3.44)$$

where $K^\mu[\varphi]$ is a functional of φ .² This is a requirement for symmetry in quantum field theory too. However, as physical quantities in quantum field theory are given not just by the action of a single state but the path integral, the integration measure $\mathcal{D}\varphi$ has to be invariant as well. If a classical symmetry fails due to the non-invariance of the integration measure, it is called an *anomaly*.

To investigate the symmetry properties of a quantum theory, we explore what constraints a symmetry imposes on the effective action. To that end, assume

$$\mathcal{D}\varphi'(x) = \mathcal{D}\varphi(x), \quad S[\varphi'] = S[\varphi]. \quad (3.45)$$

In the generating functional, such a transformation corresponds to a change of integration variable. Using the infinitesimal version of the transformation, we may write

$$\begin{aligned} Z[J] &= \int \mathcal{D}\varphi \exp \left\{ iS[\varphi] + i \int d^4x J_i(x) \varphi_i(x) \right\} = \int \mathcal{D}\varphi' \exp \left\{ iS[\varphi'] + i \int d^4x J_i(x) \varphi'_i(x) \right\} \\ &= Z[J] + i\epsilon \int d^4x J_i(x) \int \mathcal{D}\varphi [V_{ij}\varphi_j(x)] e^{iS[\varphi]}, \end{aligned} \quad (3.46)$$

Using Eq. (3.18), we can write this as

$$\int d^4x \frac{\delta \Gamma[\varphi_J]}{\delta \varphi_i(x)} V_{ij} \langle \varphi_j(x) \rangle_J = 0. \quad (3.47)$$

This constraint will allow us to deduce the properties of a theory close to the ground state, only using information about the symmetries of the theory.

The archetypical example of an internal, global, and continuous symmetry is the linear sigma model, which we will use as an example throughout this section. The linear sigma model is made up of N real scalar fields φ_i , whose Lagrangian is

$$\mathcal{L}[\varphi] = \frac{1}{2} \partial_\mu \varphi_i(x) \partial^\mu \varphi_i(x) - \mathcal{V}(\varphi), \quad \mathcal{V}(\varphi) = -\frac{1}{2} \mu^2 \varphi_i(x) \varphi_i(x) + \frac{1}{4} \lambda [\varphi_i(x) \varphi_i(x)]^2. \quad (3.48)$$

This system is invariant under the rotation of the N fields into each other,

$$\varphi_i \longrightarrow \varphi'_i = M_{ij} \varphi_j, \quad M^{-1} = M^T. \quad (3.49)$$

The set of all such transformations forms the Lie group $O(N)$. Lie groups will be discussed in the next section. For $N = 2$, and $\mu^2, \lambda > 0$ we get the ubiquitous Mexican hat potential, as illustrated in Figure 3.1.

²Terms of the form $\partial_\mu K^\mu$ does not affect the physics, as variational principle $\delta S = 0$ do not vary the fields at infinity. Together with the divergence theorem, this means that such terms do not influence the equations of motion.

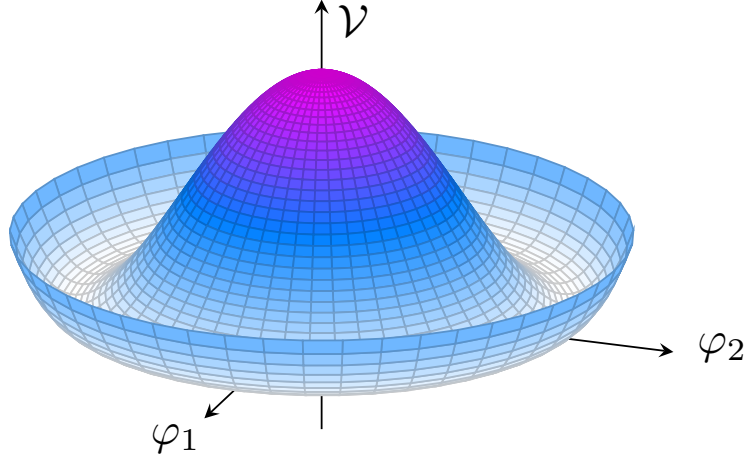


Figure 3.1: The Mexican hat potential is the classical potential \mathcal{V} for the $N = 2$ linear sigma model.

3.3.1 Nöther's theorem

One of the most profound consequences of symmetry in physics is the appearance of conserved quantities. Assume we have a set of fields φ_i . Nöther's theorem tells us that if the Lagrangian $\mathcal{L}[\varphi_i]$ has a continuous symmetry, then there is a corresponding conserved current [2, 4]. Consider an infinitesimal transformation,

$$\varphi_i(x) \longrightarrow \varphi'_i(x) = \varphi_i(x) + \delta\varphi_i(x), \quad (3.50)$$

Applying this transformation to the Lagrangian will in general change its form,

$$\mathcal{L}[\varphi] \rightarrow \mathcal{L}[\varphi'] = \mathcal{L}[\varphi] + \delta\mathcal{L}. \quad (3.51)$$

We assume this transformation is a symmetry, i.e.,

$$\delta\mathcal{L} = \partial_\mu K^\mu.$$

By considering the Lagrangian as a function of the field and its derivatives, $\mathcal{L} = \mathcal{L}(\varphi_i, \partial_\mu \varphi_i)$, we can write the difference term as a Taylor expansion around $(\varphi_i, \partial_\mu \varphi_i)$,

$$\delta\mathcal{L} = \frac{\partial\mathcal{L}}{\partial\varphi_i} \delta\varphi_i + \frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi_i)} \delta(\partial_\mu \varphi_i), \quad (3.52)$$

where $\delta(\partial_\mu \varphi_i) = \partial_\mu \varphi'_i - \partial_\mu \varphi_i$. By the linearity of the derivative,

$$\delta(\partial_\mu \varphi_i) = \partial_\mu \varphi'_i - \partial_\mu \varphi_i = \partial_\mu (\varphi'_i - \varphi_i) = \partial_\mu \delta\varphi_i. \quad (3.53)$$

With this, and the Euler-Lagrange equations

$$\partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi)} - \frac{\partial\mathcal{L}}{\partial\varphi_i} = 0, \quad (3.54)$$

we can rewrite

$$\delta\mathcal{L} = \left(\partial_\mu \frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi_i)} \right) \delta\varphi_i + \frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi_i)} (\partial_\mu \delta\varphi_i) = \partial_\mu \left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi_i)} \delta\varphi_i \right) \quad (3.55)$$

If we define the current

$$j^\mu = \frac{\partial\mathcal{L}}{\partial(\partial_\mu \varphi_i)} \delta\varphi_i(x) - K^\mu, \quad (3.56)$$

then

$$\partial_\mu j^\mu = \delta\mathcal{L} - \delta\mathcal{L} = 0. \quad (3.57)$$

This is Nöther's theorem; a continuous symmetry implies the existence of a conserved current.

The current flux through some spacelike surface V defines a conserved charge. The surface of constant time in some reference frame has the normal vector $n_\mu = (1, 0, 0, 0)$, so the charge is

$$Q = \int_V d^4x n_\mu j^\mu = \int_V d^3x j^0. \quad (3.58)$$

We can then use the divergence theorem. Assume ∂V is the boundary of V , which has the space-like normal vector k_i , and that the current falls off quickly towards infinity. Then

$$\frac{\partial Q}{\partial t} = - \int_V d^3x \partial_i j^i = - \int_{\partial V} d^2x k_i j^i = 0, \quad (3.59)$$

proving that the charge is conserved.

3.3.2 Goldstone's theorem

A symmetry transformation will leave the governing equation of a theory unchanged. This, however, does not imply that physical states, such as the ground state, are invariant under this transformation. The $N = 2$ linear sigma model illustrates this. If we assume the ground state φ_0 is translationally invariant, then it is given by minimizing the effective potential, of which the classical potential, \mathcal{V} , is the leading order approximation. This potential is illustrated in Figure 3.1. The ground state is therefore given by any of the values along the brim of the potential. If we, without loss of generality, choose $\varphi_0 = (0, v)$ as the ground state, then any rotation will change this state. We say that the symmetry has been *spontaneously broken*.

To explore this in a general context, assume a theory of N real scalar fields φ_i are invariant under the actions of some Lie group, G . A symmetry $g \in G$ is broken if the vacuum expectation value of the original fields and the transformed fields differ. That is, if

$$\langle \varphi \rangle_0 \neq \langle \varphi' \rangle_0 = \langle g\varphi \rangle_0 \quad (3.60)$$

We can now exploit what we learned about Lie groups to write the infinitesimal transformation as

$$\langle \varphi' \rangle_0 = \langle \varphi \rangle_0 + i\epsilon \eta_\alpha T_\alpha \langle \varphi \rangle_0. \quad (3.61)$$

Let x_i be the set of generators corresponding to broken symmetries, i.e.,

$$x_i \langle \varphi \rangle_0 \neq 0. \quad (3.62)$$

These are called the *broken generators*. The remaining set of generators t_a , which obey

$$t_a \langle \varphi \rangle_0 = 0, \quad (3.63)$$

are called unbroken, and generate a subgroup $H \subset G$ as the set of symmetry transformations of the vacuum is a group.

In Eq. (3.47) we found that, if V is the generator of some symmetry, then the effective action obeys

$$\int d^4x \frac{\delta \Gamma[\varphi_J]}{\delta \varphi_i} V_{ij} \langle \varphi_j \rangle_0 = 0, \quad (3.64)$$

We now differentiate this expression with respect to $\varphi_k(y)$ and evaluate it in the vacuum, which gives

$$\int d^4x \frac{\delta \Gamma[\varphi_0]}{\delta \varphi_k(y), \varphi_i(x)} V_{ij} \langle \varphi_j \rangle_0 = 0. \quad (3.65)$$

With the assumption that the ground state is constant, we get

$$\frac{\partial^2 \mathcal{V}_{\text{eff}}}{\partial \varphi_k \partial \varphi_i} V_{ij} \langle \varphi_j \rangle_0 = 0. \quad (3.66)$$

This is trivial for unbroken symmetries, as $t_{ij}^a \langle \varphi_j \rangle_0 = 0$ by definition. However, in the case of a broken symmetry, the second derivative of the effective potential has an eigenvector $x_{ij}^\ell \langle \varphi_j \rangle_0$ with a zero eigenvalue for each broken generator. Here, ℓ label the set of generators, while (ij) are the indices corresponding to field-components φ_i . In Eq. (3.24), we found that the second derivative of the effective action is the inverse propagator,

$$D_{ij}^{-1}(x, y) = \frac{\delta^2 \Gamma[\varphi_0]}{\delta \varphi_i(y) \delta \varphi_j(x)} = \int \frac{d^4 p}{(2\pi)^4} e^{-ip(x-y)} \tilde{D}_{ij}^{-1}(p). \quad (3.67)$$

Using this, we can write

$$\tilde{D}_{ij}^{-1}(p=0) x_{jk}^\ell \langle \varphi_k \rangle_0 = 0. \quad (3.68)$$

Zeros of the inverse propagator correspond to the physical mass of particles. In Lorentz-invariant systems, each zero-eigenvalue vector corresponds to a massless particle, called a Goldstone boson.³ This means there are $n_G = \dim G - \dim H$ zero-mass modes. In general, the counting of massless modes is complicated and depends on the dispersion relation of the particles at low momenta. Systems with Goldstone bosons with quadratic dispersion relation, that is $E \propto |\vec{p}|^2$ when $\vec{p} \rightarrow 0$, often exhibit a lower number of massless modes. An example is ferromagnets, where the SU(2) rotational symmetry is broken down to U(1) when they align along one axis. This corresponds to two broken generators, yet the system exhibits only one massless mode [8].

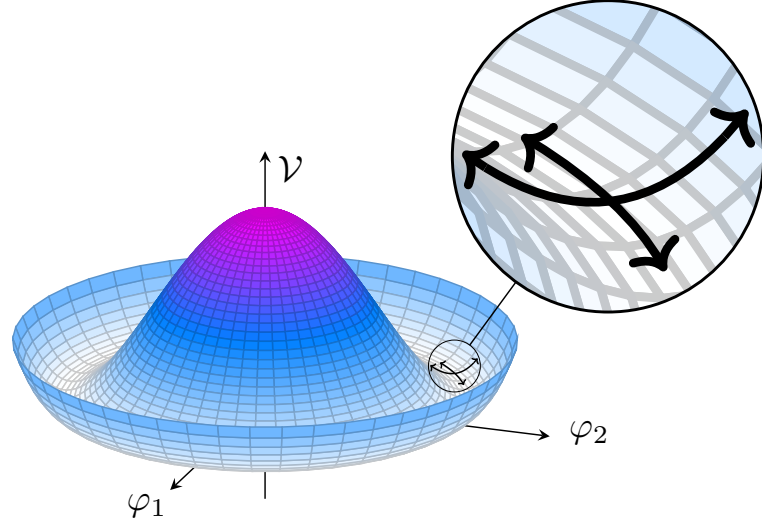


Figure 3.2: Excitations along the brim does not cost any energy, as the potential is flat, unlike excitations in the radial direction.

The linear sigma model gives an intuition for the Goldstone mode. In the case of $N = 2$, the symmetry of the Lagrangian are rotations in the plane. As the ground state is a point along the “brim” of the hat, this rotational symmetry is broken. However, any excitations in the angular direction do not cost any energy, which is indicative of a massless mode. This is illustrated in Figure 3.2. In this example, the original symmetry group is one-dimensional, so there are no unbroken symmetries. Consider instead the $N = 3$ linear sigma model, which has the three-dimensional symmetry group SO(3), rotations of the sphere. We see that the ground state is left invariant under a subgroup of the original symmetry transformations. The ground state manifold of this system, the set of all states that minimizes the effective potential, is then a sphere. When the system chooses one single ground state, this symmetry is broken, but only for two of the generators. The generator for rotations around the ground state leaves that point unchanged and is thus an unbroken symmetry. Any excitations in the direction of the broken symmetries do not cost energy, as it is in the ground state manifold. On the other hand, the unbroken symmetry does not correspond to an excitation. This is illustrated in Figure 3.3.

³The particles are bosons due to the bosonic nature of the transformations, g . If the generators are Grassmann numbers, the resulting particles, called goldstinos, are fermions.

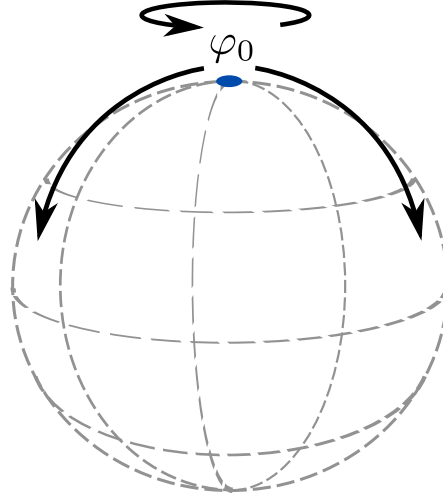


Figure 3.3: Excitations for the $N = 3$ sigma model. Two of the symmetries are broken, while rotations around the groundstate leaves the system unchanged.

3.4 CCWZ construction

As Goldstone bosons are massless, they play a crucial role in low-energy dynamics. To best describe this limit, we seek a parametrization of the theory in which they are the degrees of freedom. This can be done using the CCWZ construction, named after Callan, Coleman, Wess, and Zumino. This section is based on [6, 9–11], as well as the original papers [12, 13].

We saw that the Goldstone bosons correspond to excitations within the vacuum manifold. The vacuum manifold corresponds to points in field space φ that can be reached from the vacuum φ_0 with a transformation $g \in G$. Assume this group acts linearly on the fields. This means that we can write such excitations as

$$\varphi_i = (\tilde{\Sigma}\varphi_0)_i = \tilde{\Sigma}_{ij}(\varphi_0)_j, \quad \tilde{\Sigma} = \tilde{\Sigma}(\eta) = \exp\{i\eta_\alpha T_\alpha\} \quad (3.69)$$

We will drop the indices for the sake of compact notation. $\tilde{\Sigma}$ is thus a function from the parameter space, $\eta_\alpha \in \mathbb{R}^n$, to G ,

$$\tilde{\Sigma} : \mathbb{R}^n \mapsto G. \quad (3.70)$$

We then get space-time-dependent field configurations by making the parameters dependent on space-time. We will for now assume η_α is constant. This parametrization is highly redundant. Two elements $\tilde{\Sigma}$ and $\tilde{\Sigma}'$, related by

$$\tilde{\Sigma}' = \tilde{\Sigma} e^{i\theta_a t_a} \quad (3.71)$$

results in the same φ . This is because $e^{i\theta_a t_a} = h \in H$, and $h\varphi_0 = \varphi_0$, by assumption. The set of all equivalent $\tilde{\Sigma}$'s is exactly the left coset, $gH = \{gh \mid h \in H\}$. The set of cosets forms a new manifold, G/H , called the Goldstone manifold. This is a manifold of dimension $\dim(G/H) = \dim(G) - \dim(H)$, which is the number of broken generators and thus also the number of Goldstone modes. Membership of a certain coset form an equivalence relation, $g \sim g'$ if $g' = gh$. This means that the cosets gH form a partition of G and that each element $g \in G$ belongs to one, and only one, coset. To remove the redundancy in the parametrization, we need to choose one representative element from each coset.

By the inverse function theorem, any mapping between manifolds $f : \mathcal{M} \mapsto \mathcal{N}$ that has a non-degenerate differential, that is an invertible Jacobian, at a point $p \in \mathcal{M}$, is invertible in a neighborhood of p . If we write

$$\tilde{\Sigma}(\xi, \theta) = \exp\{i\xi_i x_i\} \exp\{i\theta_a t_a\}, \quad (3.72)$$

then the map is invertible at $p = (\xi_i = 0, \theta_a = 0)$, as the Jacobian is the identity matrix. This point is mapped to the identity element of G . This means that, in a neighborhood $U \subset G$ of the identity, each element g has a unique representation $g = \tilde{\Sigma}$ [3]. Furthermore, two elements $\tilde{\Sigma}'$ and $\tilde{\Sigma}$ related by $\tilde{\Sigma}' = \tilde{\Sigma}h$,

$h \in H$ have the same ξ -arguments. We see that ξ_i parametrize G/H , in the neighborhood of the identity. We therefore demand that $\tilde{\Sigma}$ always appear in the standard form

$$\Sigma(\xi) = \tilde{\Sigma}(\xi, 0) = \exp\{i\xi_i x_i\}. \quad (3.73)$$

The field $\varphi(x)$ can therefore be written as

$$\varphi(x) = \Sigma(x)\varphi_0 = \exp\{i\xi_i(x)x_i\}\varphi_0, \quad (3.74)$$

and $\xi_i(x)$ can be associated with the Goldstone bosons.

In the linear sigma model, the original $O(N)$ symmetry is broken down to $O(N-1)$, which transforms the remaining $N-1$ fields with vanishing expectation values into each other. However, $O(N)$ consists of two disconnected subsets, those matrices with determinant 1 and those with determinant -1. There is no continuous path that takes an element of $O(N)$ with determinant of -1 to an element with determinant 1.⁴ The set of symmetries that are connected to the identity is

$$G = SO(N) = \{M \in O(N) \mid \det M = 1\}. \quad (3.75)$$

If we choose $\varphi_0 = (0, 0, \dots, v)$, then it is apparent that the ground state is invariant under the rotations of the $N-1$ first fields, so the unbroken symmetry is $H = SO(N-1)$. The Goldstone manifold is $G/H = SO(N)/SO(N-1)$.

Consider the case of $N=3$, which is illustrated in Figure 3.3. G is the rotations of the sphere, while H is rotations around φ_0 , $SO(2)$. The Goldstone manifold consists of the rotations of φ_0 to other points of the sphere, i.e. $G/H = SO(3)/SO(2) = S^2$, the 2-sphere. This is not a Lie group, as translating φ in a closed path around the sphere may result in a rotation around the z-axis. This is illustrated in Figure 3.4

To check that ξ_i , in fact, are the Goldstone modes, we study the way they appear in the Lagrangian. As they are massless, no mass term of the form $M_{ij}\xi_i\xi_j$ should appear. The original Lagrangian $\mathcal{L}[\varphi]$ was invariant under global transformations $\varphi(x) \mapsto g\varphi(x)$. However, any terms that only depend on $\varphi(x)$, and not its derivatives, will also be invariant under a *local* transformation, $\varphi(x) \mapsto g(x)\varphi(x)$. Our parametrization of the fields, $\varphi(x) = \Sigma(x)\varphi_0$ is exactly such a transformation, which means that any such terms are independent of the Goldstone bosons. We can therefore write

$$\mathcal{L}[\varphi] = \mathcal{L}_{\text{kin}}[\varphi] + V(\varphi_0), \quad (3.76)$$

where all terms in \mathcal{L}_{kin} are proportional to at least one derivative term, $\partial_\mu\varphi(x)$. Inserting the parametrization into this derivative term, we get

$$\partial_\mu\varphi(x) = \partial_\mu[\Sigma(x)\varphi_0] = \Sigma(x)[\Sigma(x)^{-1}\partial_\mu\Sigma(x)]\varphi_0. \quad (3.77)$$

The Lagrangian will therefore depend on ξ_i via terms of the form $\Sigma(x)^{-1}\partial_\mu\Sigma(x)$, which is called the Maurer-Cartan form. This is a \mathfrak{g} -valued function, which means that it can be written as

$$i\Sigma(x)^{-1}\partial_\mu\Sigma(x) = d_\mu(x) + e_\mu(x), \quad (3.78)$$

$$d_\mu = ix_id_{ij}(\xi)\partial_\mu\xi_j, \quad (3.79)$$

$$e_\mu = it_ae_{ai}(\xi)\partial_\mu\xi_i, \quad (3.80)$$

where d_{ij} and e_{ai} are as-of-yet unknown real valued functions of ξ [6, 14].

3.4.1 Transformation properties of Goldstone bosons

We can deduce how the Goldstone bosons transforms under G from how φ transforms. In general,

$$\varphi' = g\varphi = (g\Sigma(\xi))\varphi_0 = \Sigma(\xi')\varphi_0 \quad g \in G. \quad (3.81)$$

While $\Sigma(\xi')$ has the standard form by assumption,

$$\Sigma(\xi') = \exp\{i\xi'_i x_i\}, \quad (3.82)$$

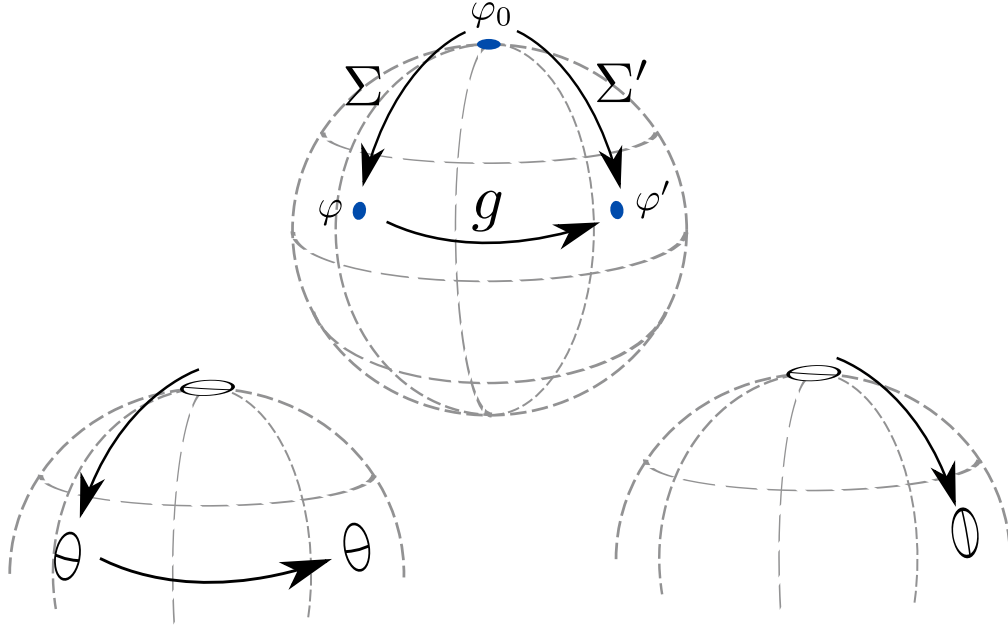


Figure 3.4: The top figure illustrates the transformation of φ_0 to φ and then φ' , and the alternative, direct transformation $\varphi_0 \rightarrow \varphi'$. The bottom figure illustrates how this can rotate a neighborhood of φ_0 differently.

$g\Sigma(\xi)$ does not, in general.

Figure 3.4 illustrates this in the case of $G = \text{SO}(3)$. $\Sigma(\xi)$ transforms φ_0 to φ , then g transforms φ to $\varphi' = \Sigma(\xi')\varphi_0$. Assuming φ and φ' are close enough to φ_0 , we can write $\Sigma(\xi)$ and $\Sigma(\xi')$ on the standard form. However, if we follow a small neighborhood around φ_0 as it is acted on by $\Sigma(\xi)$, then g , it will be rotated by the time it arrives at φ' when compared to the same neighborhood if it was acted on by $\Sigma(\xi')$.

$g\Sigma(\xi)$ and $\Sigma(\xi')$ are in the same coset, as they by assumption corresponds to the same physical state. This means that we can write $g\Sigma(\xi) = \Sigma(\xi')h(g, \xi)$, where $h(g, \xi) \in H$. The transformation rule of ξ under G is therefore implicitly defined by

$$\Sigma(\xi') = g\Sigma(\xi)[h(g, \xi)]^{-1}. \quad (3.83)$$

This is, in general, not a linear representation, which is why this construction also is called a *non-linear realization*. Using the transformation rule, we can obtain the transformation rule of the Maurer-Cartan form. We use the shorthand $\Sigma = \Sigma(\xi)$, $\Sigma' = \Sigma(\xi')$, and $h = h(g, \xi)$. This gives

$$\begin{aligned} \Sigma^{-1}\partial_\mu\Sigma &\rightarrow \Sigma'^{-1}\partial_\mu\Sigma' \\ &= (g\Sigma h^{-1})^{-1}\partial_\mu(g\Sigma h^{-1}) \\ &= (h\Sigma^{-1}g^{-1})g[(\partial_\mu\Sigma)h^{-1} + \Sigma\partial_\mu h^{-1}] \\ &= h\Sigma^{-1}(\partial_\mu\Sigma)h^{-1} + h\partial_\mu h^{-1} \\ &= h(\Sigma^{-1}\partial_\mu\Sigma + \partial_\mu)h^{-1}. \end{aligned}$$

In terms of d_μ and e_μ ,

$$d_\mu \rightarrow h d_\mu h^{-1} \quad (3.84)$$

$$e_\mu \rightarrow h(e_\mu + i\partial_\mu)h^{-1}. \quad (3.85)$$

These are our building blocks for constructing a general, G -invariant effective Lagrangian. The trace of a product of d_μ 's are invariant under G ,

$$\text{Tr}\{d_\mu d_\nu \dots d_\rho\} \rightarrow \text{Tr}\{h d_\mu h^{-1} h d_\nu h^{-1} h \dots d_\rho h^{-1}\} = \text{Tr}\{d_\mu d_\nu \dots d_\rho\}, \quad (3.86)$$

⁴A simple proof of this is the fact that the determinant is a continuous function, while any path $\det M(t)$ such that $\det M(1) = -1$, $\det M(0) = 1$ must make a discontinuous jump.

where we have used the cyclic property of trace. However, the terms must also obey the other symmetries of the Lagrangian, such as C or P-parity and Lorentz invariance. The last criterion excludes any terms with free space-time indices. In section:chiral perturbation theory, we will construct an effective Lagrangian in powers of d . The lowest order terms are therefore

$$\text{Tr}\{d_\mu\} \text{Tr}\{d^\mu\}, \quad \text{Tr}\{d_\mu d^\mu\}. \quad (3.87)$$

We see that e_μ transforms like a gauge field, with the gauge group H . If we include massive degrees of freedom and not only the Goldstone modes, e_μ is used to create a covariant derivative of the massive modes. We are only interested in the Goldstone modes and will therefore be satisfied with d_μ . With these tools, we can create an effective theory of quantum chromodynamics at low energies.

Legg til dette

Chapter 4

General relativity and the TOV equation

4.1 General relativity

(Newtonian gravity??)

Short about
newtonian
gravity/mo-
tivation

4.1.1 Einstein's field equations

General relativity describes spacetime as a smooth manifold \mathcal{M} , with a (pseudo-Riemannian) metric, $g_{\mu\nu}$. This metric is treated as a dynamical field, which is affected by the presence of matter and energy. The matter and energy contents of spacetime are encoded in the stress-energy tensor $T_{\mu\nu}$, while the behavior of $g^{\mu\nu}$ is encoded in a scalar Lagrangian density. Some of the mathematics used in this section, such as functional derivatives, are covered in section A.1.

The most obvious—and correct—choice as the Lagrangian for $g^{\mu\nu}$ is the Ricci scalar, which results in the Einstein-Hilbert action,

$$S_{\text{EH}} = \frac{1}{2\kappa} \int_{\mathcal{M}} d^n x \sqrt{|g|} R. \quad (4.1)$$

The $\sqrt{|g|}$ -factor is included for the integral to be coordinate-independent, as discussed in subsection 2.1.4.¹ The κ is a constant and decides how strong the coupling of gravity to matter and energy is. This constant can then be related to Newton's constant of gravitation G by $\kappa = 8\pi G$. When including the contributions from other fields with an action S_{m} , the total action becomes

$$S = S_{\text{EH}} + S_{\text{m}}. \quad (4.2)$$

The equations of motion of the dynamical field, which in this case is the metric, are given by Hamilton's principle of stationary action. Using functional derivatives, as defined in subsection A.1.3, this is stated as

$$\frac{\delta S}{\delta g^{\mu\nu}} = 0, \quad (4.3)$$

We define the stress-energy tensor as

$$T_{\mu\nu} = -\frac{2}{\sqrt{|g|}} \frac{\delta S_{\text{m}}}{\delta g^{\mu\nu}}. \quad (4.4)$$

¹The gravitational action can also include a cosmological constant, modifying the Lagrangian to $R + 2\Lambda$. This constant does not affect the subject of this thesis and is therefore not included here.

The functional derivative of the Einstein-Hilbert action is evaluated in subsection A.1.4, and with the result, Eq. (A.32), we get the Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \kappa T_{\mu\nu}, \quad (4.5)$$

The left-hand side of the Einstein field equations is called the Einstein tensor, $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$. This tensor obeys the identity

$$\nabla^\mu G_{\mu\nu} = 0, \quad (4.6)$$

as a consequence of the more general Bianchi identity.

4.1.2 Spherically symmetric spacetime

To model stars, we will assume that the metric is spherically symmetric and time-independent. In this case, the most general metric can be written, at least locally, as [2]

$$ds^2 = e^{2\alpha(r)} dt^2 - e^{2\beta(r)} dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2), \quad (4.7)$$

where α and β are general functions of the radial coordinate r . In matrix form, this corresponds to

$$g_{\mu\nu} = \begin{pmatrix} e^{2\alpha(r)} & 0 & 0 & 0 \\ 0 & -e^{2\beta(r)} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2(\theta) \end{pmatrix}. \quad (4.8)$$

Using Eq. (2.33), we can now compute the Christoffel symbols in terms of the unknown functions. These computations in this subsection are done using computer code, which is shown in Appendix B. The results are

$$\Gamma_{\mu\nu}^t = \begin{pmatrix} 0 & \frac{d}{dr}\alpha(r) & 0 & 0 \\ \frac{d}{dr}\alpha(r) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad (4.9)$$

$$\Gamma_{\mu\nu}^r = \begin{pmatrix} e^{2\alpha(r)}e^{-2\beta(r)}\frac{d}{dr}\alpha(r) & 0 & 0 & 0 \\ 0 & \frac{d}{dr}\beta(r) & 0 & 0 \\ 0 & 0 & -re^{-2\beta(r)} & 0 \\ 0 & 0 & 0 & -re^{-2\beta(r)}\sin^2(\theta) \end{pmatrix}, \quad (4.10)$$

$$\Gamma_{\mu\nu}^\theta = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{r} & 0 \\ 0 & \frac{1}{r} & 0 & 0 \\ 0 & 0 & 0 & -\sin(\theta)\cos(\theta) \end{pmatrix}, \quad (4.11)$$

$$\Gamma_{\mu\nu}^\phi = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{r} \\ 0 & 0 & 0 & \frac{\cos(\theta)}{\sin(\theta)} \\ 0 & \frac{1}{r} & \frac{\cos(\theta)}{\sin(\theta)} & 0 \end{pmatrix}. \quad (4.12)$$

The symbols not included are zero. Substituting these results into Eq. (2.35) gives the Riemann tensor curvature tensor. We can then obtain the Ricci tensor by taking the trace, as shown in Eq. (2.36). The results are

$$R_{tt} = \left(r \left(\frac{d}{dr}\alpha(r) \right)^2 - r \frac{d}{dr}\alpha(r) \frac{d}{dr}\beta(r) + r \frac{d^2}{dr^2}\alpha(r) + 2 \frac{d}{dr}\alpha(r) \right) \frac{e^{2\alpha(r)}e^{-2\beta(r)}}{r}, \quad (4.13)$$

$$R_{rr} = -\frac{1}{r} \left(r \left(\frac{d}{dr}\alpha(r) \right)^2 - r \frac{d}{dr}\alpha(r) \frac{d}{dr}\beta(r) + r \frac{d^2}{dr^2}\alpha(r) - 2 \frac{d}{dr}\beta(r) \right), \quad (4.14)$$

$$R_{\theta\theta} = - \left(r \frac{d}{dr}\alpha(r) - r \frac{d}{dr}\beta(r) - e^{2\beta(r)} + 1 \right) e^{-2\beta(r)}, \quad (4.15)$$

$$R_{\varphi\varphi} = R_{\theta\theta} \sin^2(\theta). \quad (4.16)$$

All other components are zero. Finally, the trace of the Ricci tensor gives the Ricci scalar,

$$R = \frac{2e^{-2\beta(r)}}{r^2} \left[r^2 \left(\frac{d}{dr} \alpha(r) \right)^2 - r^2 \frac{d}{dr} \alpha(r) \frac{d}{dr} \beta(r) + r^2 \frac{d^2}{dr^2} \alpha(r) + 2r \frac{d}{dr} \alpha(r) - 2r \frac{d}{dr} \beta(r) - e^{2\beta(r)} + 1 \right]. \quad (4.17)$$

The unknown functions α and β are now determined by the matter and energy content of the universe, which is encoded in $T_{\mu\nu}$, through Einstein's field equation, Eq. (4.5).

Skriv om
Schwarzschild-
løsningen

4.2 The TOV equation

We will model a star as being made up of a *perfect fluid*, which is entirely described by its energy density u and pressure p . The relationship between the pressure and energy density of a substance is called the *equation of state*, or EOS, and has the form

$$f(p, u, \{\xi_i\}) = 0, \quad (4.18)$$

where $\{\xi_i\}$ are possible other thermodynamic variables. We will be working at zero temperature, in which case there are no other free thermodynamic variables. This allows us to, at least locally, express the energy density as a function of the pressure, $u = u(p)$. The stress-energy tensor of a perfect fluid is

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$$T_{\mu\nu} = (u + p)u_\mu u_\nu - pg_{\mu\nu}, \quad (4.19)$$

where u_μ is the 4-velocity of the fluid. In the rest frame of the fluid, we may write

$$v_\mu = (v_0, 0, 0, 0). \quad (4.20)$$

This, together with the normalization condition of 4-velocities, $v_\mu v^\mu = 1$, allows us to calculate that

$$v_\mu v^\mu = g^{\mu\nu} v_\mu v_\nu = g^{00} (v_0)^2 = 1. \quad (4.21)$$

Using Eq. (4.8), we see that

$$v_0 = e^{\alpha(r)}. \quad (4.22)$$

This gives us the stress-energy tensor of the perfect fluid in its rest frame,

$$T_{\mu\nu} = \begin{pmatrix} u(r)e^{2\alpha(r)} & 0 & 0 & 0 \\ 0 & p(r)e^{2\beta(r)} & 0 & 0 \\ 0 & 0 & p(r)r^2 & 0 \\ 0 & 0 & 0 & p(r)r^2 \sin^2(\theta) \end{pmatrix}. \quad (4.23)$$

We will use the tt and rr components of the Einstein field equations, which are

$$8\pi G r^2 u(r) e^{2\beta(r)} = 2r \frac{d}{dr} \beta(r) + e^{2\beta(r)} - 1 \quad (4.24)$$

$$8\pi G r^2 p(r) e^{2\beta(r)} = 2r \frac{d}{dr} \alpha(r) - e^{2\beta(r)} + 1. \quad (4.25)$$

In analogy with the Schwarzschild metric, we define the function $m(r)$ by

$$e^{2\beta(r)} = \left(1 - \frac{2Gm(r)}{r} \right)^{-1}. \quad (4.26)$$

Substituting this into Eq. (4.24) yields

$$\frac{dm(r)}{dr} = 4\pi r^2 u(r). \quad (4.27)$$

The solution is simply

$$m(r) = 4\pi \int_0^r dr' r'^2 u(r'). \quad (4.28)$$

We see that $m(r)$ is the matter content contained within a radius r . If $u = 0$ for $r > R$ and $m(r > R) = M$, then the metric on a constant-time surface, i.e. $dt = 0$, is

$$ds^2 = \left(1 - \frac{2GM}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2). \quad (4.29)$$

This is the same as for the Schwarzschild solution.

Using the Bianchi identity, Eq. (4.6), together with Einstein's equation, we find

$$\nabla^\mu G_{\mu\nu} = \nabla^\mu T_{\mu\nu} = 0. \quad (4.30)$$

The r -component of this equation is

$$\begin{aligned} \nabla_\mu T^{\mu r} &= \partial_r T^{rr} + \Gamma_{\mu\nu}^\mu T^{\nu r} + \Gamma_{\mu\nu}^r T^{\mu\nu} \\ &= \partial_r (pe^{-2\beta}) + (2\Gamma_{rr}^r + \Gamma_{tr}^t)T^{rr} + \Gamma_{tt}^r T^{tt} \\ &= e^{-2\beta} (\partial_r p + p\partial_r \alpha + u\partial_r \alpha) = 0. \end{aligned}$$

This allows us to relate α to p and u , via

$$\partial_r \alpha = -\frac{\partial_r p}{p + u} \quad (4.31)$$

When we substitute this, together with the definition of $m(r)$, into Eq. (4.25), we obtain

$$\frac{dp}{dr} = -\frac{G}{r^2} (4\pi r^3 p + m) (p + u) \left(1 - \frac{2Gm}{r}\right)^{-1}, \quad (4.32)$$

the Tolman-Oppenheimer-Volkoff (TOV) equation. This equation was first obtained by Oppenheimer and Volkoff in 1939 [15] and was based on earlier work by Tolman [16]. In their paper, Oppenheimer and Volkoff studied the properties of a star made up of cold, degenerate fermions.

To summarize, we have three unknown functions, $u(r)$, $p(r)$, and $m(r)$. The equation of state, Eq. (4.18), determines $u = u(p)$, eliminating one unknown. The two differential equations Eq. (4.28) and Eq. (4.32), together with the boundary conditions $p(0) = p_c$ and $m(0) = 0$, then yield $p(r)$ and $m(r)$ when integrated. Given this, we can solve for all the unknown functions, either analytically or numerically. However, we can gain some insight into the system without solving these equations by expressing the problem in terms of dimensionless variables. We define

$$u = u_0 \tilde{u}, \quad p = p_0 \tilde{p}, \quad m = m_0 \tilde{m}, \quad r = r_0 \tilde{r}. \quad (4.33)$$

Here, quantities with subscript 0 are dimensionful constants, which may be chosen as the characteristic quantities of the problem, while the tilde indicates a dimensionless variable. By substituting this into Eq. (4.27) and Eq. (4.32), we can collect the dimensionful constants into a smaller number of dimensionless constants, k_i . These constants will decide the nature of the solution. Any change in the dimensionful constants that leave the k_i 's invariant is a scaling of the problem — it corresponds to the same solution with different units. The new differential equations are

$$\frac{d\tilde{m}}{d\tilde{r}} = 3k_2 \tilde{r}^2 \tilde{u} \quad (4.34)$$

$$\frac{d\tilde{p}}{d\tilde{r}} = -\frac{k_1}{k_3} \frac{1}{\tilde{r}^2} (k_3 \tilde{p} + \tilde{u}) (3k_2 k_3 \tilde{r}^3 \tilde{p} + \tilde{m}) \left(1 - \frac{2k_1 \tilde{m}}{\tilde{r}}\right)^{-1}, \quad (4.35)$$

where the dimensionless constants are defined as

$$k_1 = G \frac{m_0}{r_0}, \quad k_2 = \frac{4\pi}{3} \frac{r_0^3 u_0}{m_0}, \quad k_3 = \frac{p_0}{u_0}. \quad (4.36)$$

The energy density and pressure are of comparable magnitude in the relativistic regime. We will therefore often choose $k_3 = 1$, defining $p_0 = u_0$. If we have a non-complete set of characteristic quantities, the dimensionless constants k_i tell us something about the magnitude we should expect the solution to have. After defining the remaining dimensionful constants by setting $k_i = 1$, we expect that the dimensionless sizes of a typical solution will be of order 1. In other words, the dimensionful constants defined by $k_i = 1$ are new, characteristic quantities given to us by the form of the governing equation only.

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4.2.1 Newtonian limit

In the Newtonian limit, the rest energy, i.e., mass, gives the dominant contribution to the gravitational field, while the contribution from pressure is negligible. In other words, the characteristic pressure, p_0 , is far smaller than the characteristic energy density u_0 , and we can use the approximation $k_3 \ll 1$. Furthermore, the star's radius should be much larger than the Schwarzschild radius, $R_s = 2GM$. If we choose $r_0 = R$, then $k_1 \ll 1$. In this limit, the lowest-order contribution to the TOV equation is

$$\frac{d\tilde{p}}{d\tilde{r}} = -\frac{k}{\tilde{r}^2} \tilde{u} \tilde{m}, \quad k = \frac{k_1}{k_3} = G \frac{u_0 m_0}{p_0 r_0}. \quad (4.37)$$

Using the mass equation Eq. (4.34), we can write this as

$$4\pi \tilde{r}^2 \frac{d\tilde{p}}{d\tilde{m}} = -k' \frac{\tilde{m}}{\tilde{r}^2}, \quad k' = \frac{4\pi}{3} \frac{k_1}{k_2 k_3} = G \frac{m_0^2}{r_0^4 p_0}. \quad (4.38)$$

We may derive this equation directly from Newtonian gravity. Assume we have a static, gravitationally bound ball of matter, as illustrated in Figure 4.1. The force due to the pressure gradient over a thin, spherical shell, $F_p = 4\pi r^2 dp$, must be counteracted by the gravitational force on the same shell, $F_g = -Gmdm/r^2$.

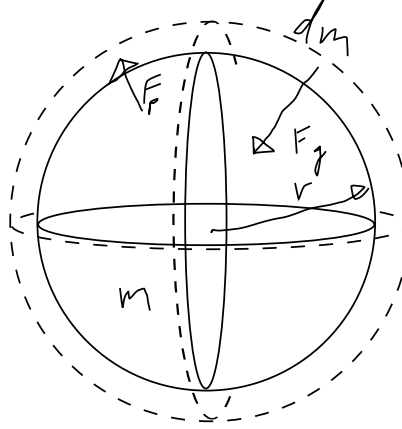


Figure 4.1: Kladd: The forces acting on a thin shell dm .

Both the Newtonian limit and the TOV equation are equations of *hydrostatic equilibrium*, where the forces on a small volume of the fluid cancel out. In the case of the TOV equation, we tacitly assumed hydrostatic equilibrium when we gave the fluid a rest frame where we could write $v_\mu = (v_0, 0, 0, 0)$ globally. We can eliminate the equation for mass by differentiating Eq. (4.37) with respect to \tilde{r} . This gives us a single equation for hydrostatic equilibrium in the Newtonian limit,

$$\frac{d}{d\tilde{r}} \left(\frac{\tilde{r}^2}{\tilde{u}} \frac{d\tilde{p}}{d\tilde{r}} \right) = -k'' \tilde{r}^2 \tilde{u}, \quad k'' = 3 \frac{k_2 k_1}{k_3} = 4\pi G \frac{u_0^2 r_0^2}{p_0}. \quad (4.39)$$

4.2.2 Incompressible fluid

The simplest model for a star is one made up of an incompressible fluid, where the energy density is independent of the pressure. In this case, the energy density of the star will be constant for a radius $r < R$, before it drops to zero,

$$u(r) = u_0 \theta(R - r), \quad (4.40)$$

where u_0 is a constant and $\theta(x)$ the Heaviside step function. We choose $r_0 = R$. Inserting this into the differential equation of the mass function, Eq. (4.34), together with the boundary condition $m(0) = 0$, yields

$$\tilde{m}(\tilde{r}) = k_2 \tilde{r}^3, \quad (4.41)$$

when $r < R$. For $r \geq R$, or $\tilde{r} \geq 1$, this relationship is simply constant $\tilde{m}(\tilde{r}) = \tilde{m}(1) = k_2$. We choose m_0 to be the gravitational mass of the star, $M = \frac{4\pi}{3} R^3 u_0$, which is equivalent to setting $k_2 = 1$. Lastly, we choose $u_0 = p_0$, so that $k_3 = 1$. With this the TOV equation, Eq. (4.35), becomes

$$\frac{d\tilde{p}}{d\tilde{r}} = -k_1 \tilde{r} \frac{(1 + \tilde{p})(1 + 3\tilde{p})}{(1 - 2k_1 \tilde{r}^2)}. \quad (4.42)$$

This is a separable ODE, and each variable may be integrated separately. Using

$$\int \frac{dx}{(1+x)(1+3x)} = \frac{1}{2} \ln \frac{3x+1}{x+1} + \text{const.}, \quad \int dx \frac{x}{1-2x^2} = \frac{1}{4} \ln(1-2x^2) + \text{const.}, \quad (4.43)$$

together with the boundary condition $p(r = R) = 0$, we get

$$\tilde{p}(\tilde{r}) = -\frac{\sqrt{1-2k_1} - \sqrt{1-2k_1\tilde{r}^2}}{3\sqrt{1-2k_1} - \sqrt{1-2k_1\tilde{r}^2}}. \quad (4.44)$$

We see that the star is entirely characterized by k_1 . In Figure 4.2, we have plotted the pressure as a function of radius for some values of k_1 . As k_1 approaches $0.4 = 4/9$, the pressure at the center of the star increases rapidly. From the denominator of Eq. (4.44) at $r \rightarrow 0$, we find the limit

$$k_1 = G \frac{M}{R} < \frac{4}{9} \quad (4.45)$$

for the pressure to remain finite. This is an absolute limit of the mass of an object given its radius or vice versa. Although this limit is derived for a particular, unrealistic case, the more general statement can be shown to hold. General relativity does not allow for a static solution with energy densities greater than this limit; any such configuration would collapse [2].

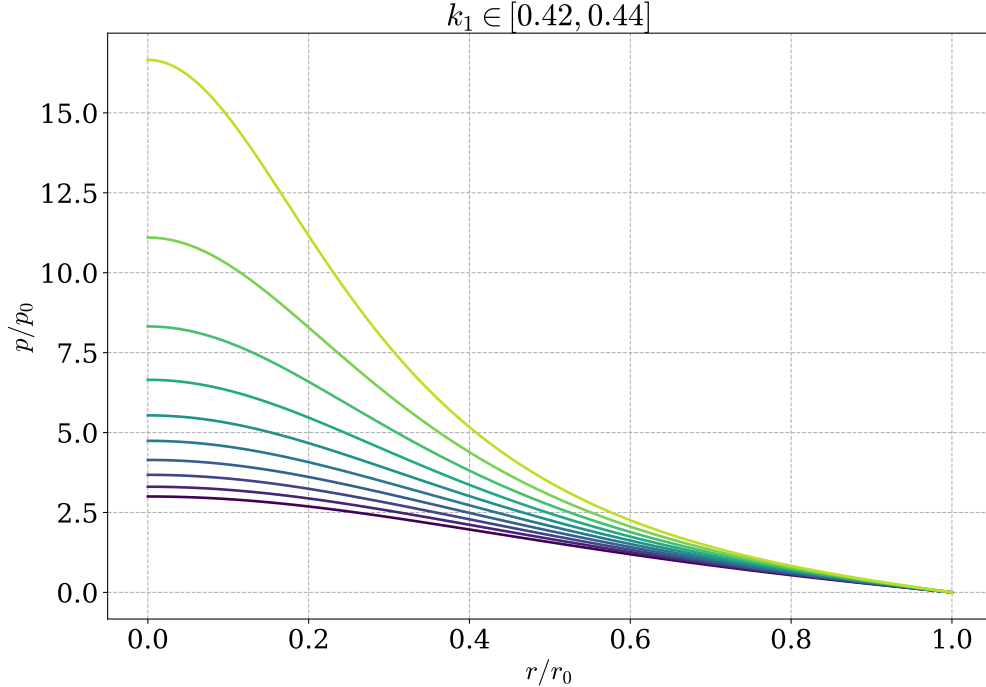


Figure 4.2: The pressure in units of p_0 , as a function of the radius, in units of r_0 . The graphs with lighter color and higher pressure at $r = 0$ corresponds to higher values of k_1 . The values of k_1 are linearly spaced.

If we expand the solution Eq. (4.44) in powers of k_1 , then the leading order contribution is

$$\tilde{p}(r) = \frac{1}{2} k_1 (1 - \tilde{r}^2). \quad (4.46)$$

This is the Newtonian limit. As a cross-check, we see that this solution obeys the equation of hydrostatic equilibrium in this limit, Eq. (4.37), as $\tilde{u} = 1$ and $k_2 = k_1 = 1$. This is the general solution for an incompressible fluid in Newtonian gravity. This solution does not have any upper limit for k_1 ; the limit $M/R < 4/9$ is purely relativistic phenomenon. In Figure 4.3, the Newtonian approximation is compared to the full, relativistic solution. We see that the Newtonian approximation is highly accurate for k_1 less than around 0.01.

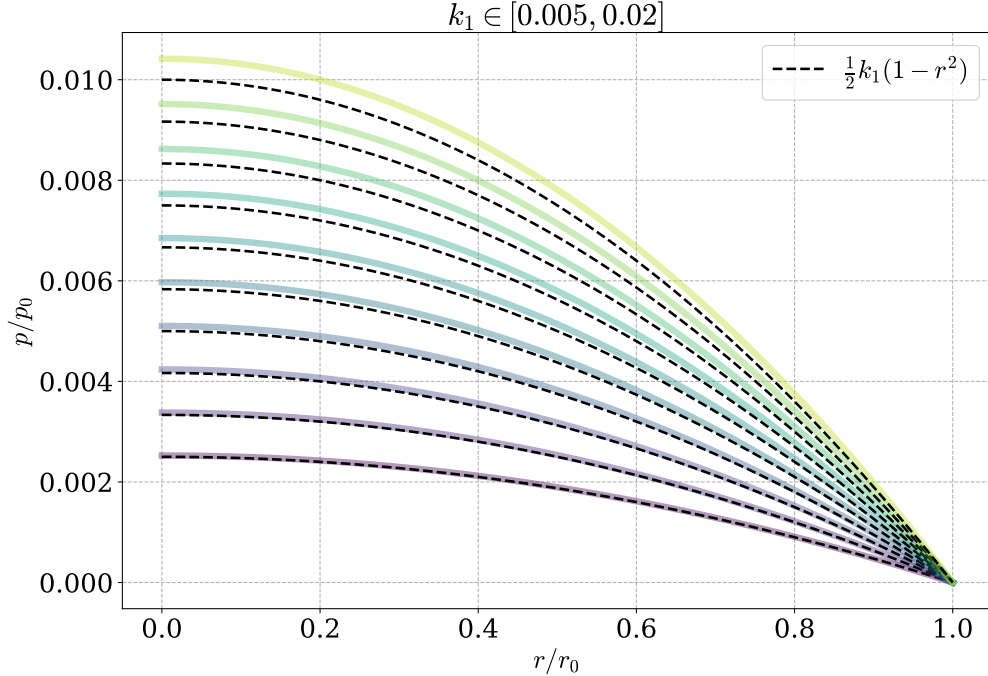


Figure 4.3: The pressure in units of p_0 , as a function of the radius, in units of r_0 . The wide, colored lines correspond to the full relativistic solution, while the dashed lines is the Newtonian approximation, for the same value of k_1 . The values of k_1 are linearly spaced.

4.3 A star of cold, non-interacting fermions

This section is based on [17–19].

4.3.1 Thermodynamics and free energy

A non-interacting Fermi gas is governed by the Dirac Lagrangian

$$\mathcal{L} = \bar{\psi}(i\cancel{\partial} - m)\psi, \quad (4.47)$$

as described in (APPENDIX thermal field theory). In the grand canonical ensemble, the density of a conserved charge is regulated by a chemical potential μ . The conserved current corresponding to the U(1) phase symmetry of the Dirac Lagrangian, i.e., the transformation $\psi \rightarrow e^{i\alpha}\psi \approx 1 + \alpha\delta\psi$, is

$$j^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \delta\psi = \bar{\psi}\gamma^\mu\psi. \quad (4.48)$$

The conserved charge is

$$Q = \int d^3x j^0 = \int d^3x \bar{\psi}\gamma^0\psi, \quad (4.49)$$

add appendix

the number of particles minus antiparticles. The total energy U is related to the grand canonical free energy F by a Legendre transformation,

$$F(T, V, \mu) = U - TS - \mu Q, \quad dF = -SdT - pdV - Qd\mu. \quad (4.50)$$

Here, p is pressure, $T = 1/\beta$ is temperature, and S entropy. These thermodynamic variables are related to the free energy by

$$S = -\frac{\partial F}{\partial T} = \beta^2 \frac{\partial F}{\partial \beta}, \quad Q = -\frac{\partial F}{\partial \mu}, \quad p = -\frac{\partial F}{\partial V}. \quad (4.51)$$

When the free energy can be written as $F = V\mathcal{F}$, where the free energy density \mathcal{F} is independent of the volume V , then $\mathcal{F} = -p$ and

$$d(V\mathcal{F}) = Vd\mathcal{F} - pdV, \quad (4.52)$$

allowing us to write

$$\mathcal{F}(T, \mu) = u - Ts - \mu n, \quad d\mathcal{F} = -sdT - nd\mu, \quad (4.53)$$

where s and n are entropy and charge density, defined by

$$s = -\frac{\partial \mathcal{F}}{\partial T} = \beta^2 \frac{\partial \mathcal{F}}{\partial \beta}, \quad n = -\frac{\partial \mathcal{F}}{\partial \mu}. \quad (4.54)$$

With this, we can write the energy density as [18]

$$u = \frac{\partial}{\partial \beta} (\beta \mathcal{F}) + \mu n. \quad (4.55)$$

4.3.2 Equation of state

The free energy density of the Fermion gas is (REF: appendix termisk)

$$\mathcal{F} = -\frac{2}{\beta} \int \frac{d^3 p}{(2\pi)^3} \left[\beta \omega + \ln \left(1 + e^{-\beta(\omega - \mu)} \right) + \ln \left(1 + e^{-\beta(\omega + \mu)} \right) \right], \quad (4.56)$$

where $\omega = \sqrt{p^2 + m^2}$. The first term in the integral is the divergent vacuum energy, which must be renormalized. We can drop this term; it does not have any observable effects on our results, as we are interested in relative pressure and energy density. With this, we find the charge density

$$n = \frac{1}{\pi^2} \int \frac{d^3 p}{(2\pi)^3} [n_f(\omega - \mu) - n_f(\omega + \mu)], \quad (4.57)$$

where

$$n_f(\omega) = \frac{1}{e^{\beta\omega} + 1}. \quad (4.58)$$

is the Fermi-Dirac distribution. The energy density is

$$u = \frac{1}{\pi^2} \int_0^\infty dp p^2 \omega [n_f(\omega - \mu) + n_f(\omega + \mu)]. \quad (4.59)$$

As expected, this is the energy per mode times the density of states, integrated over all modes. To write the pressure, $p = -\mathcal{F}$ in terms of an integral over the Fermi-Dirac distribution, we integrate by parts. We have

$$\int_0^\infty dp p^2 \ln [1 + e^{-\beta(\omega \pm \mu)}] = \frac{1}{3} p^3 \ln [1 + e^{-\beta(\omega \pm \mu)}] \Big|_0^\infty + \frac{1}{3} \int_0^\infty dp \frac{\beta p^4}{\omega} n_f(\omega \pm \mu), \quad (4.60)$$

where the boundary term vanish. This allows us to write the pressure as

$$p = \frac{1}{3} \int_0^\infty dp \frac{p^4}{\omega} [n_f(\omega - \mu) + n_f(\omega + \mu)] \quad (4.61)$$

We are interested in the $T = 0$ limit. In this case, the Fermi distribution becomes a step function, $n_f(\omega) = \theta(-\omega)$. Without loss of generality, we assume that $\mu > 0$, i.e., we are dealing with an abundance of matter compared to anti-matter. The dispersion relation $\omega = \sqrt{p^2 + m^2}$ is always positive. This means that the contribution to thermodynamic quantities from anti-particles vanish, as the integral is multiplied with $n_f(\omega + \mu) = \theta(-\omega - \mu)$, where the argument $-\omega - \mu$ is strictly negative on the domain of integration. At zero temperature, the only dynamics are due to the degeneracy pressure of the fermions, that is, due to the Pauli exclusion principle. There are no thermal fluctuations that can create a particle-antiparticle pair. Thus, if the system has a positive chemical potential, it will contain no antiparticles. Furthermore, if $\mu < m$, then integrand multiplied with $n_f(\omega - \mu)$ is also zero in the whole domain of integration. It is only when $\mu \geq m$ that it is energetically favorable for the system to be in a state with particles. We define the Fermi momentum p_f by $\mu = \sqrt{p_f^2 + m^2}$. In the zero-temperature limit, we can then rewrite any integral over the Fermi distribution as

$$\int_0^\infty dp [f(p)n_f(\omega - \mu) + g(p)n_f(\omega + \mu)] = \int_0^{p_f} dp f(p). \quad (4.62)$$

The charge density is thus,

$$n = \frac{1}{\pi^2} \int_0^{p_f} dp p^2 = \frac{p_f^3}{3\pi^2}. \quad (4.63)$$

At $T = 0$, this is the particle number density, as there are no antiparticles. This density is given by the chemical potential and vanishes when $\mu \leq m$, i.e. when the free energy cost of creating a particle is positive. We can write the energy density and pressure integrals, Eq. (4.59) and Eq. (4.61), as

$$u = \frac{1}{\pi^2} \int_0^{p_f} dp p^2 \sqrt{p^2 + m^2} = \frac{m^4}{\pi^2} \int_0^{x_f} dx x^2 \sqrt{x^2 + 1}, \quad (4.64)$$

$$p = \frac{1}{3\pi^2} \int_0^{p_f} dp \frac{p^4}{\sqrt{p^2 + m^2}} = \frac{m^4}{3\pi^2} \int_0^{x_f} \frac{dx x^4}{\sqrt{x^2 + 1}}. \quad (4.65)$$

We have defined $x = p/m$ and $x_f = p_f/m$. These integrals can be evaluated exactly as

$$\int_0^a dx x^2 \sqrt{x^2 + 1} = \frac{1}{8} \left[\sqrt{a^4 + 1} (2a^3 + a) - \operatorname{arcsinh}(a) \right], \quad (4.66)$$

$$\int_0^a dx \frac{x^4}{\sqrt{x^2 + 1}} = \frac{1}{8} \left[\sqrt{a^2 + 1} (2a^3 - 3a) + 3 \operatorname{arcsinh}(a) \right]. \quad (4.67)$$

We introduce the characteristic energy and number density,

$$u_0 = \frac{m^4}{8\pi^2}, \quad n_0 = \frac{u_0}{m}, \quad (4.68)$$

which allows us to write the thermodynamic variables as

$$n = \frac{8}{3} n_0 x_f^3 \quad (4.69)$$

$$u = u_0 \left[(2x_f^3 + x_f) \sqrt{1 + x_f^2} - \operatorname{arcsinh}(x_f) \right], \quad (4.70)$$

$$p = \frac{u_0}{3} \left[(2x_f^3 - 3x_f) \sqrt{1 + x_f^2} + 3 \operatorname{arcsinh}(x_f) \right]. \quad (4.71)$$

We have thus chosen $u_0 = p_0$, or equivalently set $k_3 = 1$. This is natural in the case of a relativistic fluid.

4.3.3 Limits

In the non-relativistic limit, as the chemical potential approaches m and thus $p_f \ll m$, the lowest order contributions to the energy density and pressure are given by the Taylor series around $x_f = 0$,

$$\tilde{u}(x_f) = \frac{8}{3} x_f^3 + \frac{4}{5} x_f^5 + \mathcal{O}(x_f^7), \quad (4.72)$$

$$\tilde{p}(x_f) = \frac{8}{15} x_f^5 + \mathcal{O}(x_f^7). \quad (4.73)$$

By neglecting terms of order x_f^7 and higher, we can write this as

$$\tilde{u} = \tilde{n} + \frac{4}{5} \left(\frac{8}{3} \tilde{n} \right)^{5/3}, \quad \tilde{p} = \frac{8}{15} \left(\frac{8}{3} \tilde{n} \right)^{5/3}. \quad (4.74)$$

The leading order contribution to the energy density is the rest mass of the particles. This term does not contribute to the pressure. As discussed earlier, the non-relativistic limit corresponds to $k_3 \ll 1$, if we chose units so that $\tilde{u} \approx \tilde{p}$, or $\tilde{u} \gg \tilde{p}$ if we demand that $k_3 = 1$. We see that $x_f \rightarrow 0$ corresponds to the latter case. By including only the leading order term, we can eliminate the Fermi momentum and write the equation of state in the non-relativistic limit as $u_{\text{nr}} = kp^{3/5}$ where $k = 8/3 \cdot (15/8)^{3/5}$. Equations of state where $u \propto p^\gamma$ are called polytropes. In the ultrarelativistic limit, where $p_f \gg m$, the leading order contributions to the pressure and energy density are

$$\tilde{u} = 2x_f^4, \quad \tilde{p} = \frac{2}{3}x_f^4, \quad (4.75)$$

and we get the particularly simple equation of state for the ultrarelativistic limit, $u_{\text{ur}} = 3p$, which we recognize as the formula for radiation pressure. The equation of state $\tilde{u}(\tilde{p})$ in two different regimes is shown in Figure 4.4. The full equation of state is compared to the non-relativistic and ultrarelativistic approximations.

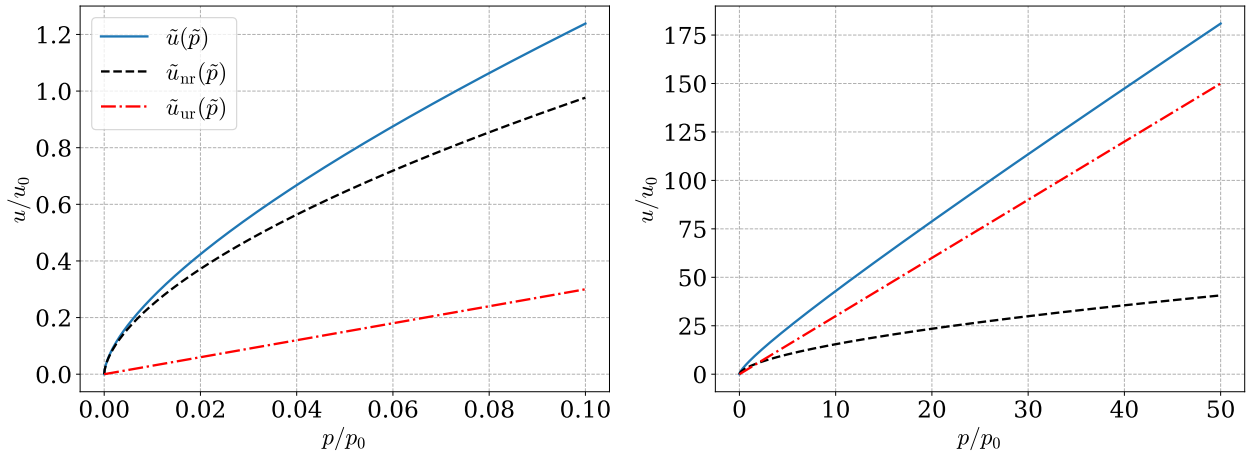


Figure 4.4: The equation of state of a cold Fermi gas. Both pressure and energy density is normalized to their characteristic quantities, p_0 and u_0 . The equation of state is compared to the non-relativistic approximation, \tilde{u}_{nr} as well as the ultrarelativistic approximation, \tilde{u}_{ur} , in two different regimes.

4.3.4 Units

The equation of state has given us the characteristic energy density and pressure, u_0 and p_0 . If we demand

$$G \frac{m_0}{r_0} = \frac{4\pi}{3} \frac{r_0^3 u_0}{m_0} = 1, \quad (4.76)$$

we have two equations and two unknowns, m_0 and r_0 . This thus defines a complete set of units. We are using the cold Fermi-gas as a model for a neutron star, and the mass of the fermion m is therefore the neutron mass, Eq. (1.7), $m_N = 1.674 \cdot 10^{-27}$ kg. After reinstating \hbar and c in metric units, we get

$$u_0 = p_0 = \frac{m^4 c^5}{8\pi^2 \hbar^3} = 2.032 \cdot 10^{35} \text{ J m}^{-3}, \quad (4.77)$$

$$m_0 = \frac{c^4}{\sqrt{\frac{4\pi}{3} u_0 G^3}} = 1.608 \cdot 10^{31} \text{ kg} = 8.082 M_\odot \quad (4.78)$$

$$r_0 = \frac{G m_0}{c^2} = 11.93 \text{ km}. \quad (4.79)$$

From this, we expect our star to have a mass of the order of a solar mass, $M_\odot = 1.98841 \cdot 10^{30}$ kg [1], and a radius of the order of kilometers, without solving the TOV equation.

4.3.5 Numerical results

With the energy density, Eq. (4.70), and pressure, Eq. (4.71), we can numerically solve the TOV equation given a central pressure p_c . This is done using an adaptive Runge-Kutta method, with the stop criterion $p(r) = 0$. Description of the code and where to find it is given in Appendix B. With our choice of units, the form of the TOV equation is

$$\frac{d\tilde{m}}{d\tilde{r}} = 3\tilde{r}^2\tilde{u}, \quad \frac{d\tilde{p}}{d\tilde{r}} = -\frac{1}{\tilde{r}^2}(\tilde{p} + \tilde{u})(3\tilde{r}^3\tilde{p} + \tilde{m}) \left(1 - \frac{2\tilde{m}}{\tilde{r}}\right)^{-1}. \quad (4.80)$$

As $r \rightarrow 0$, parts of the TOV equation Eq. (4.35) approaches a 0/0-limit, and we must take use of an approximation for numeric evaluation. The Taylor-expansion of the mass function around $\tilde{r} = 0$ is

$$\tilde{m}(r) = \tilde{m}(0) + \tilde{m}'(0)\tilde{r} + \frac{1}{2!}\tilde{m}''(0)\tilde{r}^2 + \frac{1}{3!}\tilde{m}'''(0)\tilde{r}^3 + \mathcal{O}(\tilde{r}^4). \quad (4.81)$$

One of the boundary conditions is $\tilde{m}(0) = 0$. We then use the differential equation for \tilde{m} , Eq. (4.27), to find

$$\tilde{m}'(0) = 0, \quad \tilde{m}''(0) = 0, \quad \tilde{m}'''(0) = 6k_2\tilde{u}_0, \quad (4.82)$$

where $\tilde{u}_0 = \tilde{u}(r = 0)$. We get an approximation of the TOV equation for $\tilde{r} \ll 1$ by substituting the \tilde{m} for its Taylor expansion and including only the leading-order term, which gives

$$\frac{d\tilde{p}}{d\tilde{r}} \sim -\tilde{r}(\tilde{p} + \tilde{u})(3\tilde{p} + \tilde{u}_0)(1 - 2\tilde{u}_0\tilde{r}^2)^{-1}, \quad r \rightarrow 0 \quad (4.83)$$

For the Newtonian approximation to the TOV equation, we get

$$\frac{d\tilde{p}}{d\tilde{r}} = -\frac{\tilde{u}\tilde{m}}{\tilde{r}^2} \sim -\tilde{u}\tilde{u}_0\tilde{r}, \quad r \rightarrow 0. \quad (4.84)$$

The top graph in Figure 4.5 shows the pressure, normalized to the central pressure p_c , as a function of radius, normalized to the corresponding stellar radius R . The stellar radius, R , is defined as the point where the pressure drops to zero, i.e., $p(R) = 0$. The boundary conditions are logarithmically spaced. The lower graph in Figure 4.5 shows the mass, normalized to the total mass $M = m(R)$, as a function of the radius, again normalized to the stellar radius. As in the case of an incompressible fluid, the pressure follows a half bell-shaped curve, with a peak that becomes narrower as the central pressure increases. The black dashed line corresponds to the solution with the maximum mass. We see that the pressure and mass curves change most drastically for central pressures higher than that which corresponds to the most massive star.

In Figure 4.6, we see the relationship between the mass and radius. This line is parameterized by the base-10 logarithm of the central pressure, $p(0)$, normalized by $p_0 = u_0$. The cross marks the maximum mass, $M_{\max} = 0.711 M_{\odot}$, which corresponds to a radius of $R = 9.20$ km. This matches the results obtained by Oppenheimer and Volkoff [15], $M_{\max} = 0.71$. In their 1939 paper, Oppenheimer and Volkoff computed five data points in the mass-radius plane. The results are marked by blue circles in Figure 4.6. We find good agreement between the three points closest to the maximum value and our results. However, the two results of Oppenheimer and Volkoff furthest away differ significantly from our results. The black dashed line is the absolute mass-radius constraint, Eq. (4.45), and any stable configuration must be on the right side of this line.

Hvorfor er to punkter så langt unna?

In Figure 4.7, we compare the mass-radius relationship obtained from the full theory with results from approximations. The lowest line is obtained by using both the full TOV equation and the equation of state. The middle line is obtained using the non-relativistic equation of state together with the full TOV equation. The upper line is from the Newtonian approximation to the TOV equation and the non-relativistic equation of state. This last approximation does not seem to have an upper limit for the mass, as expected.

Comment on instabillity

Comment why radius decrease with mass. Can this be shown in the Newtonian limit?

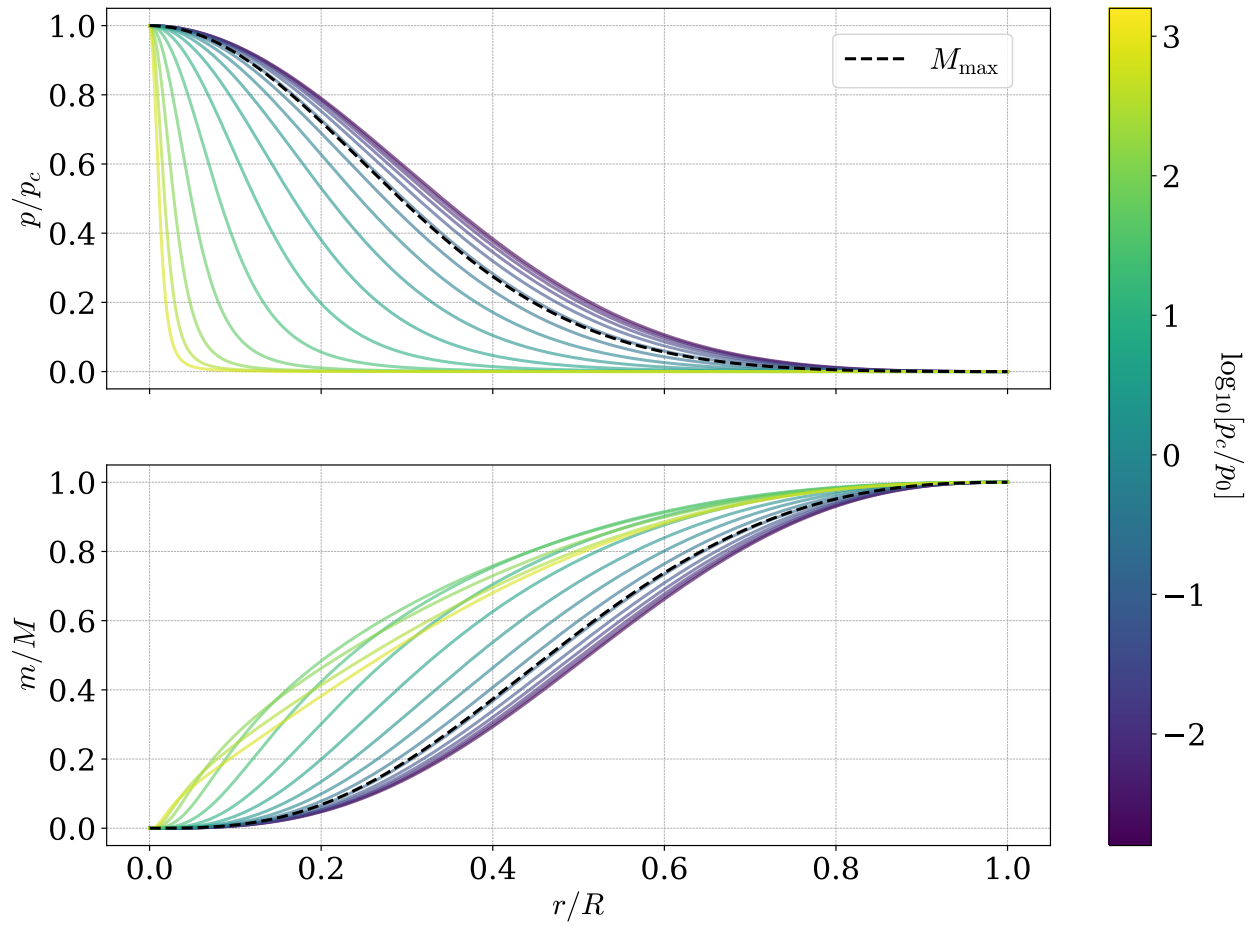


Figure 4.5: Top: The pressure normalized to central value, as a function of radius, normalized to the stellar radius. Bottom: The mass normalized to the total mass, as a function of radius, normalized to the stellar radius. This is plotted for several different values of central pressure, which is indicated by the color scheme.

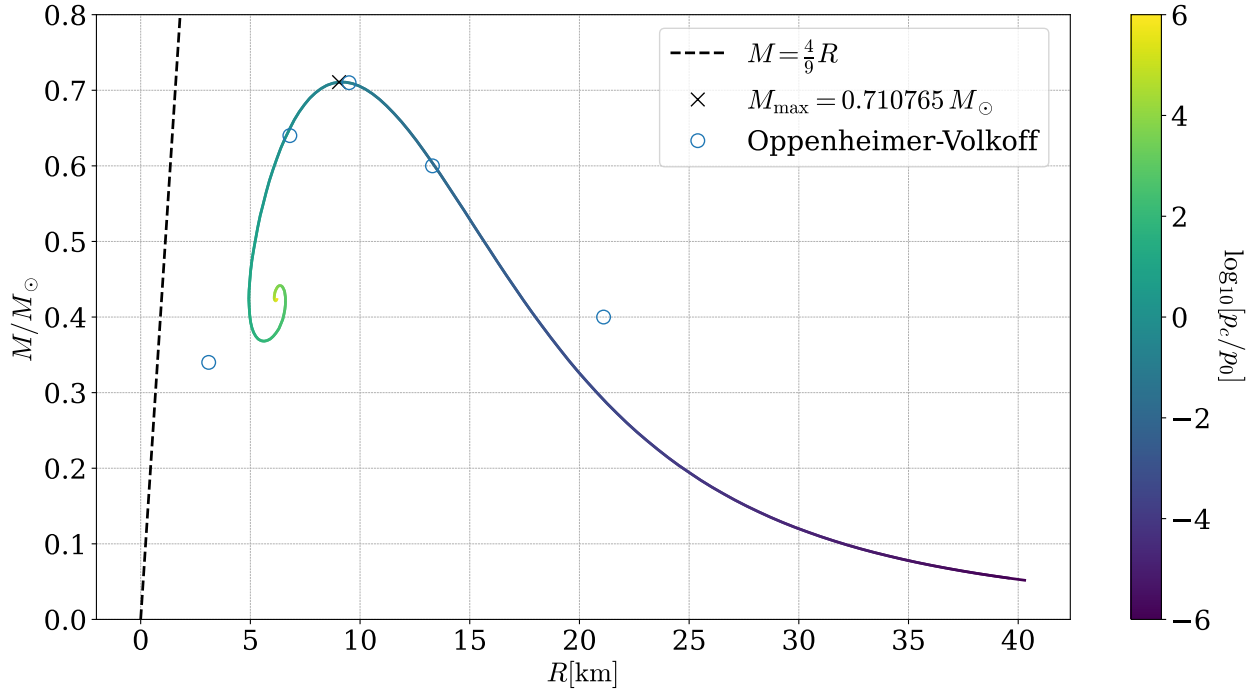


Figure 4.6: The mass-radius relationship of a star made of a cold gas of neutrons. The line is parametrized by the central pressure p_c . The cross indicate the maximum mass solution. The blue circles are results from the 1939 paper of Oppenheimer and Volkof [15].

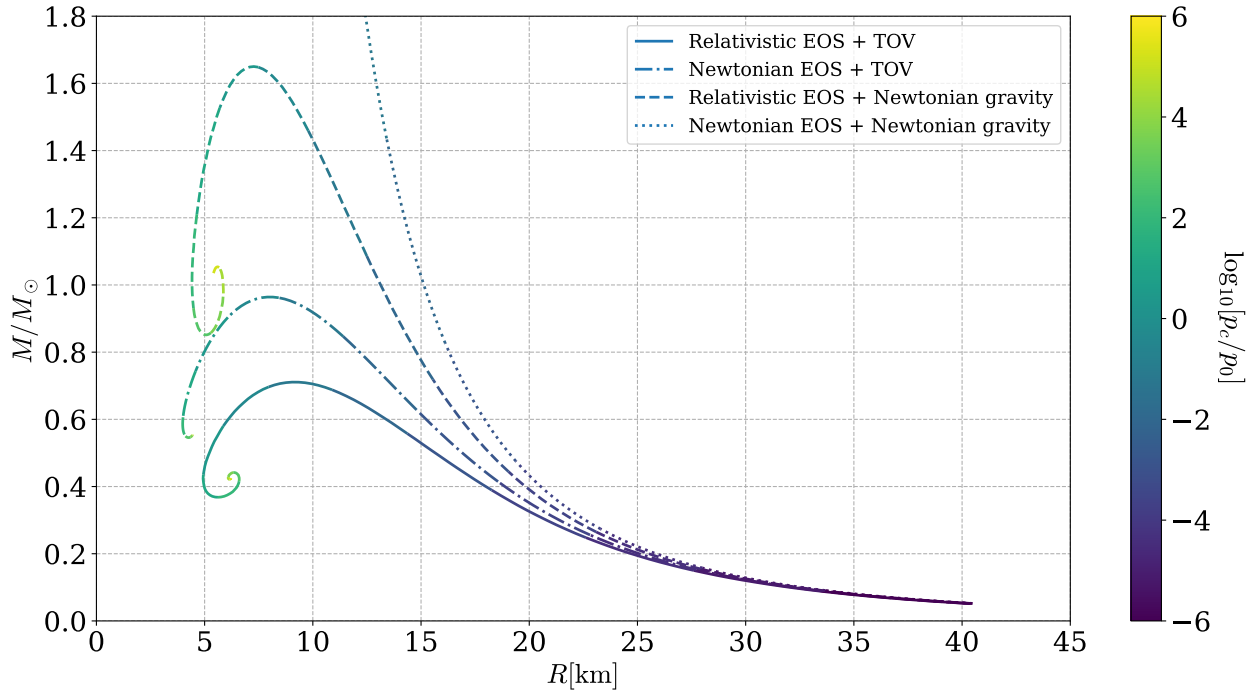


Figure 4.7: The mass-radius relationship of a cold gas of neutrons. The lowest line is obtained from the TOV equation and full equation of state. The middle line is from the TOV equation and the non-relativistic equation of state. The upper line is obtained from the Newtonian approximation of the TOV equation and the non-relativistic equation of state.

Appendix A

A.1 Functionals

(TODO: INKLUDER KILER!!!!)

The principle of stationary action and the path integral method relies on functional calculus, where ordinary, n -dimensional calculus is generalized to an infinite-dimensional calculus on a space of functions. A functional, S , takes in a function $\varphi(x)$, and returns a real number $S[\varphi]$. We will be often be dealing with functionals of the form

$$S[\varphi] = \int_{\mathcal{M}} d^n x \mathcal{L}[\varphi](x), \quad (\text{A.1})$$

Here, $\mathcal{L}[\varphi](x)$, the Lagrangian density, is a functional which takes in a function φ , and returns a real number $\mathcal{L}[\varphi](x)$ for each point $x \in \mathcal{M}$. Thus, \mathcal{L} does, in fact, return a real-valued function, not just a number. \mathcal{M} is the manifold, in our case space-time, of which both $\varphi(x)$ and $\mathcal{L}[\varphi](x)$ are functions. The function φ can, in general, take on the value of a scalar, complex number, spinor, vector, etc..., while $\mathcal{L}[\varphi](x)$ must be a scalar-valued function. This strongly constraints the form of any Lagrangian and is an essential tool in constructing quantum field theories. Although this section is written with a single scalar-valued function φ , this can easily be generalized by adding an index, $\varphi \rightarrow \varphi_\alpha$, enumerating all the degrees of freedom, then restating the arguments [2, 7].

A.1.1 Functional derivative

The functional derivative is base on an arbitrary *variation* η of the function φ . The variation η , often written $\delta\varphi$ is an arbitrary function only constrained to vanish *quickly enough* at the boundary $\partial\mathcal{M}$.¹ The variation of the functional S is defined as

$$\delta_\eta S[\varphi] = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} (S[\varphi + \epsilon\eta] - S[\varphi]) = \frac{d}{d\epsilon} S[\varphi + \epsilon\eta]|_{\epsilon=0}. \quad (\text{A.2})$$

We can regard the variation of a functional as the generalization of the differential of a function, Eq. (2.18), as the best linear approximation around a point. In regular differential geometry, a function f can be approximated around a point x by

$$f(x + \epsilon v) = f(x) + \epsilon df(v), \quad (\text{A.3})$$

where v is a vector in the tangent space at x . In functional calculus, the functional S is analogous to f , φ to x , and η to v . We can more clearly see the resemblance by writing

$$\frac{d}{d\epsilon} f(x + \epsilon v) = df(v) = \frac{\partial f}{\partial x^\mu} v^\mu. \quad (\text{A.4})$$

In the last line we expanded the differential using the basis-representation, $v = v^\mu \partial_\mu$. To generalize this to functional, we define the *functional derivative*, by

$$\delta_\eta S[\varphi] = \int_{\mathcal{M}} d^n x \frac{\delta S[\varphi]}{\delta \eta(x)} \eta(x). \quad (\text{A.5})$$

¹The condition of “quickly enough” is to ensure that we can integrate by parts and ignore the boundary condition, which we will do without remorse.

If we let $S[\varphi] = \varphi(x)$, for some fixed x , the variation becomes

$$\delta_\eta S[\varphi] = \eta(x) = \int d^n y \delta(x - y) \eta(y), \quad (\text{A.6})$$

which leads to the identity

$$\frac{\delta \varphi(x)}{\delta \varphi(y)} = \delta(x - y). \quad (\text{A.7})$$

There is also a generalized chain rule for functional derivatives. If ψ is some new functional variable, then

$$\frac{\delta S[\varphi]}{\delta \varphi(x)} = \int_{\mathcal{M}} d^n y \frac{\delta S[\varphi]}{\delta \psi(y)} \frac{\delta \psi(y)}{\delta \varphi(x)}. \quad (\text{A.8})$$

Higher functional derivatives are defined in terms of higher-order variations,

$$\delta_\eta^m S[\varphi] = \frac{d}{d\epsilon} \delta_\eta^{m-1} S[\varphi + \epsilon \eta]|_{\epsilon=0} = \int_{\mathcal{M}} \left(\prod_{i=1}^m d^n x_i \eta(x_i) \right) \frac{\delta^m S[\varphi]}{\delta \varphi(x_1) \dots \delta \varphi(x_m)}. \quad (\text{A.9})$$

With this, we can write the functional Taylor expansion,

$$S[\varphi_0 + \varphi] = S[\varphi_0] + \int_{\mathcal{M}} d^n x \varphi(x) \frac{\delta S[\varphi_0]}{\delta \varphi(x)} + \frac{1}{2} \int_{\mathcal{M}} d^n x d^n y \varphi(x) \varphi(y) \frac{\delta^2 S[\varphi_0]}{\delta \varphi(x) \delta \varphi(y)} + \dots \quad (\text{A.10})$$

Here, the notation $\delta S[\varphi_0]/\delta \varphi$ indicate that $S[\varphi]$ is first differentiated with respect to φ , then evaluated at $\varphi = \varphi_0$ [4].

A.1.2 The Euler-Lagrange equation

The Lagrangian may also be written as a scalar function of the field-values at x , $\varphi(x)$, as well as its derivatives, $\partial_\mu \varphi(x)$, for example

$$\mathcal{L}(\varphi, \partial_\mu \varphi) = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{1}{4!} \lambda \varphi^4 + \dots \quad (\text{A.11})$$

We have omitted the evaluation at x for the brevity of notation. We use this to evaluate the variation of a functional in the of Eq. (A.1),

$$\delta_\eta S[\varphi] = \frac{d}{d\epsilon} \int_{\mathcal{M}} d^n x \mathcal{L}[\varphi + \epsilon \eta](x), \quad (\text{A.12})$$

by Taylor expanding the Lagrangian density as a function of φ and its derivatives,

$$\mathcal{L}[\varphi + \epsilon \eta] = \mathcal{L}(\varphi + \epsilon \eta, \partial_\mu \{\varphi + \epsilon \eta\}) = \mathcal{L}[\varphi] + \epsilon \left(\frac{\partial \mathcal{L}}{\partial \varphi} \eta + \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi)} \partial_\mu \eta \right) + \mathcal{O}(\epsilon^2). \quad (\text{A.13})$$

Inserting this into Eq. (A.12) and partially integrating the last term allows us to write the variation in the form Eq. (A.5), and the functional derivative is

$$\frac{\delta S}{\delta \varphi} = \frac{\partial \mathcal{L}}{\partial \varphi} - \partial_\mu \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi)}. \quad (\text{A.14})$$

The principle of stationary action says that the equation of motion of a field obeys $\delta_\eta S = 0$. As η is arbitrary, this is equivalent to setting the functional derivative of S equal to zero. The result is the Euler-Lagrange equations of motion [7],

$$\frac{\partial \mathcal{L}}{\partial \varphi} - \partial_\mu \frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi)} = 0. \quad (\text{A.15})$$

A.1.3 Functional calculus on a curved manifold

As discussed in subsection 2.1.4, when integrating a scalar on a curved manifold, we must include the $\sqrt{|g|}$ -factor to get a coordinate-independent result. The action in curved spacetime is therefore [2]

$$S[g, \varphi] = \int_{\mathcal{M}} d^n x \sqrt{|g|} \mathcal{L}[g, \varphi], \quad (\text{A.16})$$

where the action and the Lagrangian now is a functional of both the matter-field φ and the metric $g_{\mu\nu}$. Our example Lagrangian from last section now takes the form

$$\mathcal{L}(g_{\mu\nu}, \varphi, \nabla_\mu \varphi) = \frac{1}{2} g^{\mu\nu} \nabla_\mu \varphi \nabla_\nu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{1}{4!} \lambda \varphi^4 \dots, \quad (\text{A.17})$$

where partial derivatives are substituted with covariant derivatives. We define the functional derivative as

$$\delta_\eta S = \int_{\mathcal{M}} d^n x \sqrt{|g|} \frac{\delta S}{\delta \eta(x)} \eta(x). \quad (\text{A.18})$$

If this is a variation in φ only, this gives the same result as before. However, in general relativity, the metric itself is a dynamic field, and we may therefore vary it. Consider $g_{\mu\nu} \rightarrow g_{\mu\nu} + \delta g_{\mu\nu}$. The variation of the action is then assuming \mathcal{L} only depends on g and not its derivatives, we get

$$\delta_g S = \int_{\mathcal{M}} d^n x \left[\left(\delta \sqrt{|g|} \right) \mathcal{L}[g] + \sqrt{|g|} \delta \mathcal{L}[g] \right] \quad (\text{A.19})$$

We have used

$$\delta \sqrt{|g|} = -\frac{1}{2} \sqrt{|g|} g_{\mu\nu} \delta g^{\mu\nu} \quad (\text{A.20})$$

The variation of the $\sqrt{|g|}$ -factor can be evaluated using the Levi-Civita symbol $\varepsilon_{\mu_1 \dots \mu_n}$, a determinant of a $n \times n$ -matrix may be written as

$$\det(A) = \frac{1}{n!} \varepsilon_{\mu_1 \dots \mu_n} \varepsilon^{\nu_1 \dots \nu_n} A^{\mu_1}_{\nu_1} \dots A^{\mu_n}_{\nu_n}. \quad (\text{A.21})$$

Using this, we can write for a matrix M

$$\det(\mathbb{1} + \varepsilon M) = \frac{1}{n!} \varepsilon_{\mu_1 \dots \mu_n} \varepsilon^{\nu_1 \dots \nu_n} (\mathbb{1} + \varepsilon M)^{\mu_1}_{\nu_1} (\mathbb{1} + \varepsilon M)^{\mu_2}_{\nu_2} \dots \quad (\text{A.22})$$

$$= \frac{1}{n!} \varepsilon_{\mu_1 \dots \mu_n} \varepsilon^{\nu_1 \dots \nu_n} [\delta^{\mu_1}_{\nu_1} \dots + \varepsilon (M^{\mu_1}_{\nu_1} \delta^{\mu_2}_{\nu_2} \dots + M^{\mu_2}_{\nu_2} \delta^{\mu_1}_{\nu_1} \dots + \dots) + \dots] \quad (\text{A.23})$$

$$= 1 + M^\mu_\mu + \mathcal{O}(\varepsilon^2) \quad (\text{A.24})$$

Thus,

$$\delta \sqrt{|g|} = \sqrt{|\det[g_{\mu\nu}(\delta^\nu_\rho + g^{\nu\sigma} \delta g_{\sigma\rho})]|} - \sqrt{|g|} = \sqrt{|g|} \left(\sqrt{|1 + g^{\mu\nu} \delta g_{\mu\nu}|} - 1 \right) = -\frac{1}{2} \sqrt{|g|} g^{\mu\nu} \delta g_{\mu\nu}. \quad (\text{A.25})$$

The minus sign is included as the determinant of a Lorentzian metric is negative. Assuming the Lagrangian only depends on the metric directly, and not its derivatives, the variation of the action is

$$\delta_g S = \int_{\mathcal{M}} d^n x \sqrt{|g|} \left(\frac{\partial \mathcal{L}}{\partial g^{\mu\nu}} - \frac{1}{2} g_{\mu\nu} \mathcal{L} \right) \delta g^{\mu\nu}. \quad (\text{A.26})$$

With the Lagrangian in Eq. (A.17), we get

$$\frac{\delta S}{\delta g^{\mu\nu}} = \frac{\partial \mathcal{L}}{\partial g^{\mu\nu}} - \frac{1}{2} g_{\mu\nu} \mathcal{L} = -\frac{1}{2} \left(\frac{1}{2} \nabla_\mu \varphi \nabla_\nu \varphi + \frac{1}{2} m^2 \varphi^2 + \dots \right). \quad (\text{A.27})$$

We recognize the $(\mu, \nu) = (0, 0)$ -component as negative half the Hamiltonian density, which supports the definition of the stress-energy tensor Eq. (4.4).

A.1.4 Functional derivative of the Einstein-Hilbert action

(NEEDS MORE CLEANUP)

In the Einstein-Hilbert action, Eq. (4.1), the Lagrangian density is $\mathcal{L} = kR = kg^{\mu\nu}R_{\mu\nu}$, where k is a constant and $R_{\mu\nu}$ the Ricci tensor, Eq. (2.36). As the Ricci tensor is dependent on both the derivative and second derivative of the metric, we can not use Eq. (A.27) directly. Instead, we use the variation

$$\delta S_{\text{EH}} = k \int_{\mathcal{M}} d^n x \sqrt{|g|} \left(\delta R - \frac{1}{2} g_{\mu\nu} R \delta g^{\mu\nu} \right). \quad (\text{A.28})$$

The variation of the Ricci scalar is

$$\delta R = R_{\mu\nu} \delta g^{\mu\nu} + g^{\mu\nu} \delta R_{\mu\nu}, \quad (\text{A.29})$$

We can write the variation of the Ricci scalar, and thus the Riemann curvature tensor, in terms of variations in Christoffel symbols, $\delta\Gamma_{\mu\nu}^\rho$ using the explicit formula for a symmetric, metric-compatible covariant derivative, Eq. (2.35). As $\delta\Gamma = \Gamma - \Gamma'$, it is a tensor, and we may write

$$\begin{aligned} \delta R^\rho_{\sigma\mu\nu} &= \delta(\partial_{[\mu}\Gamma_{\nu]\sigma}^\rho + \Gamma_{\lambda[\mu}^\rho\Gamma_{\nu]\sigma}^\lambda) = \partial_{[\mu}\delta\Gamma_{\nu]\sigma}^\rho + (\delta\Gamma_{\lambda[\mu}^\rho)\Gamma_{\nu]\sigma}^\lambda + \Gamma_{\lambda[\mu}^\rho(\delta\Gamma_{\nu]\sigma}^\lambda) \\ &= \partial_\mu\delta\Gamma_{\nu\sigma}^\rho + \Gamma_{\lambda\mu}^\rho(\delta\Gamma_{\nu\sigma}^\lambda) - \Gamma_{\mu\sigma}^\lambda(\delta\Gamma_{\lambda\nu}^\rho) - \left(\partial_\nu\delta\Gamma_{\mu\sigma}^\rho + \Gamma_{\lambda\nu}^\rho(\delta\Gamma_{\mu\sigma}^\lambda) - \Gamma_{\nu\sigma}^\lambda(\delta\Gamma_{\lambda\mu}^\rho) \right) + (\Gamma_{\mu\nu}^\lambda\delta\Gamma_{\lambda\sigma}^\rho - \Gamma_{\mu\nu}^\lambda\delta\Gamma_{\lambda\sigma}^\rho) \\ &= \nabla_\mu\delta\Gamma_{\nu\sigma}^\rho - \nabla_\nu\delta\Gamma_{\mu\sigma}^\rho = \nabla_\eta(g^\eta_\mu\delta\Gamma_{\nu\sigma}^\rho - g^\eta_\nu\delta\Gamma_{\mu\sigma}^\rho) = \nabla_\eta(K^\rho_{\sigma\mu\nu})^\eta, \end{aligned}$$

where K is a tensorial quantity, which vanish at the boundary of our spacetime. Using the generalized divergence theorem, Eq. (2.48), we see that the contribution to the action from this quantity vansih. The contribution comes from an integral over $g^{\mu\nu}\delta R_{\mu\nu} = g^{\mu\nu}\delta R^\rho_{\mu\rho\nu} = g^{\mu\nu}\nabla_\eta(K^\rho_{\mu\rho\nu})^\eta$ Using metric compatibility, we can exchange the covariant derivative and the metric, and we have $g^{\mu\nu}\delta R_{\mu\nu} = \nabla_\eta[g^{\mu\nu}K^{\eta\rho}_{\mu\rho\nu}]$. The contribution to the action therefore becomes

$$\int_{\mathcal{M}} d^4 x \sqrt{|g|} g^{\mu\nu} \delta R_{\mu\nu} = \int_{\mathcal{M}} d^4 x \sqrt{|g|} \nabla_\eta [g^{\mu\nu} K^{\eta\rho}_{\mu\rho\nu}] = \int_{\partial\mathcal{M}} d^3 y \sqrt{|\gamma|} n_\eta [g^{\mu\nu} K^{\eta\rho}_{\mu\rho\nu}] = 0, \quad (\text{A.30})$$

where we used the fact that $\delta g_{\mu\nu}$, and thus K , vanish at $\partial\mathcal{M}$. The variation of the action is therefore

$$\delta S_{\text{EH}} = k \int_{\mathcal{M}} d^n x \sqrt{|g|} \left[R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \right] \delta g^{\mu\nu}, \quad (\text{A.31})$$

and by the definition of the functional derivative,

$$\frac{\delta S_{\text{EH}}}{\delta g^{\mu\nu}} = k(R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}). \quad (\text{A.32})$$

clean up

Appendix B

Code

All code is available at: <https://github.com/martkjoh/master>.

B.1 Integrating the TOV equations

B.2 Spherically symmetric metric

Describe the numerical code for the TOV equations

The calculations in chapter 4 were done using a CAS system. The code is written in Python in a Jupyter notebook. The full `.ipynb` file with executable code is available in the repository, at <https://github.com/martkjoh/master/blob/main/scripts/TOV.ipynb> Below is some of the code, which illustrates the main functions and the outputs.

1 Metric $g_{\mu\nu}$ for spherically symmetric spacetime

```
[8]: t, r, th, ph = symbols("t, r, \\theta, \\phi")
x1 = r * cos(ph) * sin(th)
x2 = r * sin(ph) * sin(th)
x3 = r * cos(th)

one = Rational(1)
eta = sp.diag(one, -one, -one, -one)
var = (t, r, th, ph)
J = Matrix([t, x1, x2, x3]).jacobian(var)
g = np.array(simplify(J.T * eta * J))

a = sp.Function("\\alpha", real=True)(r)
b = sp.Function("\\beta", real=True)(r)
g[0, 0] *= exp(2 * a)
g[1, 1] *= exp(2 * b)
g_inv = get_g_inv(g)

print_matrix(g)
print_matrix(g_inv)
```

$$\begin{bmatrix} e^{2\alpha(r)} & 0 & 0 & 0 \\ 0 & -e^{2\beta(r)} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2(\theta) \end{bmatrix}$$

$$\begin{bmatrix} e^{-2\alpha(r)} & 0 & 0 & 0 \\ 0 & -e^{-2\beta(r)} & 0 & 0 \\ 0 & 0 & -\frac{1}{r^2} & 0 \\ 0 & 0 & 0 & -\frac{1}{r^2 \sin^2(\theta)} \end{bmatrix}$$

```
[9]: C = Christoffel(g, g_inv, var)
c = print_christoffel(C, var)
```

$$\Gamma_{\mu\nu}^t = \begin{bmatrix} 0 & \frac{d}{dr}\alpha(r) & 0 & 0 \\ \frac{d}{dr}\alpha(r) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Gamma_{\mu\nu}^r = \begin{bmatrix} e^{2\alpha(r)}e^{-2\beta(r)}\frac{d}{dr}\alpha(r) & 0 & 0 & 0 \\ 0 & \frac{d}{dr}\beta(r) & 0 & 0 \\ 0 & 0 & -re^{-2\beta(r)} & 0 \\ 0 & 0 & 0 & -re^{-2\beta(r)}\sin^2(\theta) \end{bmatrix}$$

$$\Gamma_{\mu\nu}^\theta = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{r} & 0 \\ 0 & \frac{1}{r} & 0 & 0 \\ 0 & 0 & 0 & -\sin(\theta)\cos(\theta) \end{bmatrix}$$

$$\Gamma_{\mu\nu}^\phi = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{r} \\ 0 & 0 & 0 & \frac{\cos(\theta)}{\sin(\theta)} \\ 0 & \frac{1}{r} & \frac{\cos(\theta)}{\sin(\theta)} & 0 \end{bmatrix}$$

```
[10]: Rie = Riemann_tensor(C, var)
Ricci = contract(Rie, num_indx=4, upper=1, indx=(0, 2))

for i in range(4):
    print_scalar(Ricci[i, i].factor())
```

$$\frac{\left(r\left(\frac{d}{dr}\alpha(r)\right)^2 - r\frac{d}{dr}\alpha(r)\frac{d}{dr}\beta(r) + r\frac{d^2}{dr^2}\alpha(r) + 2\frac{d}{dr}\alpha(r)\right)e^{2\alpha(r)}e^{-2\beta(r)}}{r}$$

$$-\frac{r\left(\frac{d}{dr}\alpha(r)\right)^2 - r\frac{d}{dr}\alpha(r)\frac{d}{dr}\beta(r) + r\frac{d^2}{dr^2}\alpha(r) - 2\frac{d}{dr}\beta(r)}{r}$$

$$-\left(r\frac{d}{dr}\alpha(r) - r\frac{d}{dr}\beta(r) - e^{2\beta(r)} + 1\right)e^{-2\beta(r)}$$

$$-\left(r\frac{d}{dr}\alpha(r) - r\frac{d}{dr}\beta(r) - e^{2\beta(r)} + 1\right)e^{-2\beta(r)}\sin^2(\theta)$$

```
[11]: R = contract(Ricci, g_inv=g_inv, upper=0).simplify()
      print_scalar(R)
```

$$\frac{2 \left(r^2 \left(\frac{d}{dr} \alpha(r) \right)^2 - r^2 \frac{d}{dr} \alpha(r) \frac{d}{dr} \beta(r) + r^2 \frac{d^2}{dr^2} \alpha(r) + 2r \frac{d}{dr} \alpha(r) - 2r \frac{d}{dr} \beta(r) - e^{2\beta(r)} + 1 \right) e^{-2\beta(r)}}{r^2}$$

```
[12]: G = Ricci - Rational(1, 2) * R * g
      for i in range(4):
          G[i, i] = G[i, i].simplify().factor()
      print_scalar(G[i, i])
```

$$\frac{(2r \frac{d}{dr} \beta(r) + e^{2\beta(r)} - 1) e^{2\alpha(r)} e^{-2\beta(r)}}{r^2}$$

$$\frac{2r \frac{d}{dr} \alpha(r) - e^{2\beta(r)} + 1}{r^2}$$

$$r \left(r \left(\frac{d}{dr} \alpha(r) \right)^2 - r \frac{d}{dr} \alpha(r) \frac{d}{dr} \beta(r) + r \frac{d^2}{dr^2} \alpha(r) + \frac{d}{dr} \alpha(r) - \frac{d}{dr} \beta(r) \right) e^{-2\beta(r)}$$

$$r \left(r \left(\frac{d}{dr} \alpha(r) \right)^2 - r \frac{d}{dr} \alpha(r) \frac{d}{dr} \beta(r) + r \frac{d^2}{dr^2} \alpha(r) + \frac{d}{dr} \alpha(r) - \frac{d}{dr} \beta(r) \right) e^{-2\beta(r)} \sin^2(\theta)$$

1.0.1 Stress-energy tensor $T_{\mu\nu}$ for perfect fluid

```
[13]: p = sp.Function("p")(r)
      u = sp.Function("u")(r)

      UU = np.zeros((4, 4), dtype=sp.Rational)
      UU[0, 0] = exp(2 * a)

      T = (p + u) * UU - p * g
      for i in range(4):
          T[i, i] = T[i, i].simplify()
      print_matrix(T)
```

$$\begin{bmatrix} u(r)e^{2\alpha(r)} & 0 & 0 & 0 \\ 0 & p(r)e^{2\beta(r)} & 0 & 0 \\ 0 & 0 & r^2p(r) & 0 \\ 0 & 0 & 0 & r^2p(r)\sin^2(\theta) \end{bmatrix}$$

2 Einstein's field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$

```
[14]: G_newton = sp.Symbol("G")

eq = []
for i in range(len(G)):
    eq.append((G[i, i] - 8 * pi * G_newton * T[i, i]).simplify())

# Some manual simplification
Rtt = sp.Symbol("R_{\\theta} \\theta}")
eq[0] = eq[0] * r**2 / exp(2 * a)/exp(-2*b) * (-1)
eq[1] = eq[1] * r**2 * (-1)
eq[2] = eq[2] / r / exp(-2*b)
eq[3] = eq[3].subs(eq[2], Rtt)
for i in range(len(G)):
    print_eq(eq[i].simplify())
```

$$8\pi Gr^2u(r)e^{2\beta(r)} - 2r\frac{d}{dr}\beta(r) - e^{2\beta(r)} + 1 = 0$$

$$8\pi Gr^2p(r)e^{2\beta(r)} - 2r\frac{d}{dr}\alpha(r) + e^{2\beta(r)} - 1 = 0$$

$$-8\pi Grp(r)e^{2\beta(r)} + r\left(\frac{d}{dr}\alpha(r)\right)^2 - r\frac{d}{dr}\alpha(r)\frac{d}{dr}\beta(r) + r\frac{d^2}{dr^2}\alpha(r) + \frac{d}{dr}\alpha(r) - \frac{d}{dr}\beta(r) = 0$$

$$R_{\theta\theta}re^{-2\beta(r)}\sin^2(\theta) = 0$$

Define $e^{2\beta} = [1 - 2Gm(r)/r]^{-1}$

```
[15]: m = sp.Function("m", Real=True)(r)
      f = (1 - 2 * G_newton * m / r)**(-1)
      eq1 = (eq[0] * exp(- 2 * a)).simplify().subs(b, Rational(1, 2) * log(f)).
      ↪simplify().expand().simplify()
      s = sp.solve(eq1, m.diff(r))
      eq1 = m.diff(r) - s[0]
```

Use $\nabla_\mu T^{\mu r} = 0 \implies (p + \rho)\partial_r \alpha = -\partial_r p$.

```
[16]: eq2 = (eq[1] * r**2).subs(exp(2 * b), f).simplify()
      s = sp.solve(eq2, a.diff(r))
      eq2 = a.diff(r) - s[0]
      eq2 = ((a.diff(r) - s[0]).subs(a.diff(r), - p.diff(r) / (p + u))*(p + u)).
      ↪simplify()
      s = sp.solve(eq2, p.diff())
      eq2 = p.diff(r) - s[0].factor()
```

The TOV-equation and equation for $m(r)$, both expressions are equal to 0.

```
[17]: print_eq(eq1)
      print_eq(eq2)
```

$$-4\pi r^2 u(r) + \frac{d}{dr} m(r) = 0$$

$$\frac{G(4\pi r^3 p(r) + m(r))(p(r) + u(r))}{r(-2Gm(r) + r)} + \frac{d}{dr} p(r) = 0$$

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