# Notes related to the Nahm's equations and hyperkähler quotient constructions reading group

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Hopefully I will tex up notes on some of the topics that we cover during our reading group following [1]. I don't mean to suggest that I will make exhaustive notes or even any notes on most of the discussions. However, I will try and include the important points that we discuss. A webpage containing the details of the reading group and links to further references is available here. Depending how quickly we progress we may also try to understand the hyperkähler quotient construction of the moduli space of solutions to Hitchin's equations following [2], I have previously made some notes on aspects of this topic based on a talk that I gave at the 2017 BIG workshop on Higgs bundles.

## 1  Week 1: 1/06/2022

We had a general house keeping meeting where we decided that we wanted to read [1] and understand the example of an infinite dimensional hyperkähler quotient construction coming from Nahm's equations. For the 8th, 15th, and 22nd of June I have booked room 707 for us to use.

## 2  Week 2: 8/06/2022

I will give some general motivation and discuss the dimensional reduction of the ASD equations to give BPS monopole, Hitchin equations, and the Nahm equations. It will roughly follow section 2 of [1].

A sketch of what we discussed is included here, if I have the time I will try to flesh it out in more detail and address some of the comments that I have added.

### General Motivation/ Why Quotients

The idea of why we care about quotients is easiest to see in the finite dimensional case where we have a Lie group acting on a manifold $G \circlearrowleft M$, if this action is "nice" then the "unique" configurations are given by the quotient $M/G$. The natural physics setting for this is gauge theory[1] The ingredients are

- Manifold $M$,

- Lie group $G$ (assumed compact),

- Principal $G$-bundle $P \to M$ (and its associated vector bundles $E \to M$ usually the adjoint representation),

- gauge field are connections on $P$, the space of gauge fields, $\mathcal{A}$, is an affine space modelled on the $\mathfrak{g}$ valued 1-forms (often written $\Omega_P^1(\mathfrak{g})$),

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[1]It also shows up in lots of other cases, e.g. translation or rotation symmetries in physical theories. However, these are all finite dimensional examples. The natural source of infinite dimensional group actions on infinite dimensional spaces is in gauge theory.

- Acting on $\mathcal{A}$ is the group of gauge transformations $\mathcal{G}$, these are sections of the Adjoint bundle, when $P$ is trivial

$$\mathcal{G} = \{g : M \to G\} = C^\infty(M, G), \tag{2.1}$$

- $\mathcal{G} \circlearrowleft \mathcal{A}$ as

$$A \mapsto A^g = gAg^{-1} + gdg^{-1}. \tag{2.2}$$

The connections of interest will solve an equation coming from an energy functional: e.g. when $G = SU(2)$ and $M = \mathbb{R}^4$ take

$$E = -\frac{1}{8\pi^2} \int \mathrm{Tr}\left(F \wedge \star F\right), \tag{2.3}$$

The critical points of this energy are connections $A$ such that $d_A \star F_A = 0$, while the absolute minima are called instantons and satisfy the ASD equations $F_A = -\star F_A$ with energy $E = k \in Z$. If $A$ is an instanton then $A^g$ is also an instanton with the same energy $k$. (If $A$ satisfies any boundary conditions then they may only be preserved by $g \in \mathcal{G}_0$ e.g. $g \to \mathbb{I}$ asymptotically[2]). Then "physical" configurations are given by

$$\{A \in \mathcal{A} | d_A \star F_A = 0\}/\mathcal{G}_0, \tag{2.4}$$

and "physical" instantons with energy $k$ are in the moduli space

$$\mathcal{M}_k = \{A \in \mathcal{A} | F_A = -\star F_A\}/\mathcal{G}_0. \tag{2.5}$$

The question that we want to answer in this reading group is "How are these quotients computed?" If everything was finite dimensional there is a standard theory that could be applied however, $\dim \mathcal{A} = $ "$\infty$" $= \dim \mathcal{G}_0$, so how do we know that $\mathcal{M}_k$ is even a manifold?

This can be proved, however it is done in a case by case basis. e.g.

- YM on a Riemann surface [3],

- Hitchin equations on a Riemann surface [2],

- Moduli space of magnetic monopoles on $\mathbb{R}^3$ [4] (this case is really done by making use of the Nahm transform and computing the moduli space of solutions to Nahm's equations which is exactly the problem that we will study in this reading group).

**Instantons all the way down**

Instantons are solitons in four dimensions by imposing symmetries on them we get other interesting objects, see Table 1 for what happens to translationally invariant instantons.

| Manifold | $\mathbb{R}^4$ | $\mathbb{R}^3$ | $\mathbb{R}^2$ | $\mathbb{R}^1$ | $\mathbb{R}^0$ |
|---|---|---|---|---|---|
| Coordinates | $(x^0, x^1, x^2, x^3)$ | $(x^1, x^2, x^3)$ | $(x^0, x^1)$ | $(x^0)$ | None |
| Invariances | None | $x^0$ | $x^2, x^3$ | $x^1, x^2, x^3$ | $x^0, x^1, x^2, x^3$ |
| Fields | $A$ | $A, \Phi = A_0$ | $A, \Phi = (A_3 - iA_2)\frac{dz}{2}$ | $A_0, \vec{A}$ | $A_i$ |
| ASD eqs | $F_A = -\star F_A$ | $F_A = \star d_A\Phi$ | $\bar{\partial}_A\Phi = F_A + [\Phi, \Phi^*]$ | Nahm equations | ADHM equations |

Table 1: Instantons and their descendents.

These different dimensional instantons are not independent, some of them are related to each other through the Nahm transform. I may add more on this later depending on if we discuss the Nahm transform more in this reading group.

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[2] or at least $g$ is asymptotically in the same connected component as the identity.

## Dimensional reductions

## Instantons

## BPS monopoles

## Hitchin System

## Nahm equations

Consider $\mathbb{R}^4 = M = \mathbb{R} \times \mathbb{R}^3$ and impose invariance on the $\mathbb{R}^3$. An instanton on $\mathbb{R}^4$, and teh associated bundle $P$ descend to $\mathbb{R}$ where the instanton becomes

$$A_0 dx^0 + A_1 dx^1 + A_2 dx^2 + A_3 dx^3 = A + A_i dx^i. \tag{2.6}$$

Since $A_i : \mathbb{R} \to \mathfrak{g}$ combine them into a "Higgs field"

$$\Phi = A_1 i + A_2 j + A_3 k : \mathbb{R} \to \mathfrak{g} + \mathrm{Im}\mathbb{H}. \tag{2.7}$$

Often the notation $T_0, \vec{T}$ is used rather than $A_0, A_i$ but I will try to stick with the notation used in [1].

The ASD equations reduce to

$$\star \, d_A \Phi + \frac{1}{2}[\Phi, \Phi] = 0, \tag{2.8}$$

or

$$\dot{A}_i + [A_0, A_i] + \frac{1}{2}\varepsilon_{ijk}[A_j, A_k] = 0, \tag{2.9}$$

where we sum over $j, k$ and there is an equation for each $i = 1, 2, 3$. Checking this dimensional reduction explicitly is left as an exercise to the especially interested reader.

The action of the group of gauge transformations preserves Eq. (2.9), and $g \in \mathcal{G}$ acts on an element of $\mathcal{A}$ as

$$g \cdot (A_0, \vec{A}) = \left(\mathrm{Ad}_g A_0 - \dot{g}g^{-1}, \mathrm{Ad}_g \vec{A}\right), \tag{2.10}$$

N.B. this matches ths earlier definition of a gauge transformation since $dgg^{-1} = -gdg^{-1}$.

When $G$ is a unitary group e.g. $U(n)$ it is useful to think of the associated rank $n$ vector bundle $E \to I = [0, 1]$. We have swapped to considering Nahm over a compact interval[3] as that is the most commonly studied case in the literature. Following on from Jakob's question this seems to be because monopoles on $\mathbb{R}^3$ correspond to Nahm equations on $I$, the specifics follow from looking at the details of the Nahm transform if we cover this later I will add the details. Then

$$A_0 \to \nabla : \Omega_I^0(E) \to \Omega_I^1(E) \tag{2.11}$$

becomes a connection on a vector bundle and the $A_i$ are skew adjoint sections of $\mathrm{End}\,(E)$, in trivialisation they are just skew adjoint matrices. If the coordinate on $I$ is $t$ then Nahm's equations become

$$\nabla_t A_i + \frac{1}{2}\varepsilon_{ijk}[A_j, A_k] = 0. \tag{2.12}$$

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[3]Here the interval is $[0, 1]$ which matches the conventions in section 2 of [1], however in many places when we carry out the Nahm transform of a monopole we get the interval to be $[-1, 1]$.

The group of gauge transformations are now the automorphisms of $E$ which preserve the hermitian metric, $\mathcal{G} = \mathrm{Aut}_0(E)$, $g \in \mathcal{G}$ acts by conjugation on $\nabla_t$ and on $\vec{A}$.

**Example 2.1.** Let $G = SU(2)$ and take its basis to be $\sigma_1, \sigma_2, \sigma_3 \in \mathfrak{su}(2)$ such that $[\sigma_i, \sigma_j] = \varepsilon_{ijk}\sigma_k$ e.g. $\sigma_i = -\frac{i}{2}\tau_i$ for $\tau_i$ the Pauli matrices.

Then $\left(0, \frac{\vec{\sigma}}{t}\right)$ is a solution to Eq. (2.12) with a first order pole at $t = 0$. More generally, there are solutions in terms of Jacobi elliptic functions given in terms of an elliptic modulus $0 \leq k \leq 1$ and a parameter $0 \leq D \leq 2K(k)$, for $K(k)$ the complete elliptic integral of the second kind. Taking

$$(A_0, A_1, A_2, A_3) = (0, f_1\sigma_1, f_2\sigma_2, f_3\sigma_3) \tag{2.13}$$

Nahm's equations reduce to the Euler-Poinsot equations for a spinning top which are solved by

$$f_1(t) = \frac{D\,\mathrm{cn}_k(Dt)}{\mathrm{sn}_k(Dt)}, \tag{2.14}$$

$$f_2(t) = \frac{D\,\mathrm{dn}_k(Dt)}{\mathrm{sn}_k(Dt)}, \tag{2.15}$$

$$f_3(t) = \frac{D}{\mathrm{sn}_k(Dt)}. \tag{2.16}$$

These solutions also have first order poles at $t = 0$ and for $D \to 0$ these reduce to the initial examples. When $D = 2K(k)$ there is also a pole at $t = 1$, and when $k \to 0$ these become trigonometric

$$f_1(t) = \frac{D\cos(Dt)}{\sin(Dt)}, \tag{2.17}$$

$$f_2(t) = f_3(t) = \frac{D}{\sin(Dt)}. \tag{2.18}$$

Acting on these solutions with the group of gauge transformations,

$$\mathcal{G}_0 = \{g : I \to G | g(0) = \mathbb{I}\} \tag{2.19}$$

and by an $SO(3)$ action known as hyperkähler rotation[4] gives all the $SU(2)$ solutions to Nahm's equations with these poles and residues.

## 3 Week 3:15/06/2022

Jaime gave a run through of hyperkähler geometry and the various quotient constructions

**Hyperkähler manifolds**

**Definition 3.1.** *A Hyperkähler (HK) manifold is a smooth manifold $M$ with a Riemannian metric $g$ and three complex structures $I, J, K$ which are Kähler with respect to $g$ and satisfy $IJK = -1$.*

**Remark 3.2.** *$I, J, K$ behave like the quaternions $i, j, k$ and we have that $T_pM$ is a quaternionic space $\forall p \in M$. We also have that the dimension of $M$ is a multiple of 4, $\dim M = 4n$.*

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[4]this is the action $q \in SP(1) \subset \mathbb{H}^* \; A \mapsto q \cdot A = qAq^{-1}$ which is an $SO(3)$ action since $q$ and $-q$ act the same on $A$.

The three Kähler structures give us three symplectic structures $\omega_I, \omega_J, \omega_K$. By singling out one of the complex structures we can turn the other two into a holomorphic symplectic structure $\omega_{\mathbb{C}}$ which is holomorphic symplectic with respect to $(M, g, I, \omega_I)$. This means that HK manifolds are holomorphic symplectic manifolds.

**Remark 3.3.** *They can be defined as Riemannian manifolds with holonomoy in the compact symplectic group $Sp(n) \subset GL(4n, \mathbb{R})$. Note that the holomorphic symplectic interpretation arises because $Sp(n) = Sp(2n, \mathbb{C}) \cap U(2n)$.*

## Riemannian quotients

**Theorem 3.4.** *Let $(M, g)$ be a Riemannian manifold and $G$ a compact Lie group. If $G \circlearrowright M$ freely through isometries then $M/G$ inherits a unique Riemannian metric $\bar{g}$ such that*

$$\bar{g}(X, Y) \circ \pi = g(X^*, Y^*) \tag{3.1}$$

*$\forall X, Y \in \Gamma\left(T\left(M/G\right)\right)$ and $X^*, Y^*$ the horizontal lift to $\Gamma\left(TM\right)$. Moreover, if $(M, g)$ is complete the $(M/g, \bar{g})$ is complete.*

The idea is to build on this type of quotients by considering group actions which preserve other structures on $M$.

## Kähler quotients

Consider a Kähler manifold $(M, g, \omega, I)$ and a compact Lie group $G \circlearrowright M$ freely[5] preserving both the metric and the Kähler structure. The example to have in mind is $U(1) \circlearrowright \mathbb{C}^n$ where the action is

$$e^{i\theta} \cdot (z_1, \dots, z_n) \mapsto (e^{i\theta} z_1, \dots e^{i\theta} z_n). \tag{3.2}$$

Be aware that this action is not free, the origin is a fixed point.

As a first step consider symplectic reduction. Let $x \in \mathfrak{g}$ and $x^{\#} \in \Gamma\left(TM\right)$ be the associated infinitesimal action. Saying that the $G$ action preserves the symplectic sturcture means that

$$0 = \mathcal{L}_{x^{\#}} \omega = i_{x^{\#}} d\omega + d\left(i_{x^{\#}} \omega\right) = \left(i_{x^{\#}} \omega\right). \tag{3.3}$$

Thus $i_{x^{\#}} \omega$ is a closed one-form. If it is exact then

$$i_{x^{\#}} \omega = d\mu_x \tag{3.4}$$

and the action is called Hamiltonian, $\mu_x$ is called a Hamiltonian function, and $x^{\#}$ a Hamiltonian vector field. Combining all the generators of $\mathfrak{g}$ gives a map

$$\mu : M \to \mathfrak{g}^*, \qquad \mu : p \mapsto (x \mapsto \mu_p(x)). \tag{3.5}$$

If this map is $G$ equivariant with respect to the coadjoint action on $\mathfrak{g}^*$ then $\mu$ is called a moment map.

Going back to our example of $U(1) \circlearrowright \mathbb{C}^n$, the symplectic form is $\omega = \frac{i}{2} \sum_{i=1}^n dz_i \wedge d\bar{z}_i$ and the vector field generating the infinitesimal action is

$$x^{\#} = X = i \sum_{j=1}^n \left( z_j \frac{\partial}{\partial z_j} - \bar{z}_j \frac{\partial}{\partial \bar{z}_j} \right) \tag{3.6}$$

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[5]If the action has fixed points as in the example of $U(1) \circlearrowright \mathbb{C}^n$ a quotient can still be taken if the fixed point is removed, or if we are careful about which level set we work on.

Computing the moment map gives

$$d\mu = i_X\omega = -\sum_{i=1}^{n}(z_i d\bar{z}_i + \bar{z}_i dz_i) = d\left(-\frac{1}{2}\|z\|^2 + c\right), \tag{3.7}$$

where $c$ is an arbitrary constant. Typically $c = 1$ is taken so that $\mu^{-1}(0)$ gives the sphere with $\|z\|^2 = 2$ rather than just a point. This subtlety is due to the action having a fixed point.

If the action is free then $\mu^{-1}(0)$ is a smooth submanifold with an inclusion $\iota : \mu^{-1}(0) \hookrightarrow M$. The pullback $\iota^*\omega$ on $\mu^{-1}(0)$ is in general degenerate. However, the symplectic complement of the tangent space $T_p\mu^{-1}(0)$ is the same as the tangent space to the orbit through the point $p$ $T_p(G \cdot p)$. Thus the degenerate directions come from the directions along the orbit and quotienting by $G$ removes the degeneracy. Hence

$$M//G = \mu^{-1}(0)/G \tag{3.8}$$

inherits a symplectic form $\bar{\omega}$ defined through $\pi^*\bar{\omega} = \iota^*\omega$ where $\pi : \mu^{-1}(0) \to \mu^{-1}(0)/G$. Thus $(M//G, \bar{\omega})$ is a symplectic manifold of dimension $\dim M//G = \dim M - 2\dim G$. If $M$ has a complex structure $I$ then this descends to a complex structure $\bar{I}$ with integrability preserved, and $(M//G, \bar{g}, \bar{\omega}, \bar{I})$ is called the Kähler reduction.

In the $U(1) \circlearrowright \mathbb{C}^n$ example we saw that the level set $\mu^{-1}(0) = S^{2n-1} \subset \mathbb{C}^n$ and thus

$$C^n//U(1) = \mu^{-1}(0)/U(1) = S^{2n-1}/U(1) = \mathbb{C}P^{n-1}. \tag{3.9}$$

This is true for every level except the one where $\|z\|^2 = 0$, e.g. $\mu^{-1}(c)$, this is why we need the constant $c$ for $\mu^{-1}(0)$ to be a suitable level set.

Warning, this is sketchier as it is something that we do not understand as well as the previous topics. An alternative picture of Kähler quotients is possible if the $G$ action extends to a holomorphic action of $G_\mathbb{C}$. This is the group with Lie algebra $\mathfrak{g}_\mathbb{C} = \mathfrak{g} \otimes \mathbb{C}$ such that $G \subset G_\mathbb{C}$ is the maximum compact subgroup[6] We believe that this is unique. The action extending is equivalent to $Ix^\#$ being complete $\forall x \in \mathfrak{g}$ e.g. $Ix^\#$ gives the imaginary infinitesimal action. Then

$$M//G = M^{ss}/G_\mathbb{C}, \tag{3.10}$$

where the $ss$ superscript denotes the semistable points of $M$, e.g. we have excluded the "bad" orbits like fixed points.

Consider $U(1)_\mathbb{C} \circlearrowright \mathbb{C}^2$, then $(\mathbb{C}^n)^{ss]} = \mathbb{C}\backslash\{0\}$ since the only "bad" point is the fixed point at the origin. Then

$$(\mathbb{C}\backslash\{0\})/\mathbb{C}^* = \mathbb{C}P^n = \mathbb{C}^n U(1). \tag{3.11}$$

## HK quotients

Let $(M, g, I, J, K)$ be a HK manifold and $G$ a compact Lie group acting freely[7] on $M$ preserving the HK structure. We could hope to get a triple of moment maps, one for each symplectic/ complex structure,

$$\mu = (\mu_I, \mu_J, \mu_K) : M \to \mathfrak{g}^* \otimes \mathrm{Im}\mathbb{H}. \tag{3.12}$$

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[6]As an example think of $(U(1)^n)_\mathbb{C} = (\mathbb{C}^*)^n$. Note that this $G_\mathbb{C}$ action will not necessarily preserve all of the structure e.g. $U(1)_\mathbb{C} = \mathbb{C}^* \circlearrowright \mathbb{C}^n$ preserves the complex structure but not the metric.

[7]Again usually freely as we can deal with some "badly" behaved orbits.

e.g We need to have three Hamiltonian functions.

Then observe that $\mu_{\mathbb{C}} = \mu_J + I\mu_K : M \to \mathfrak{g}_{\mathbb{C}}^*$ is holomorphic with respect to $I$ and $\mu^{-1}(0) \subset M$ is a Kähler submanifold of $(M, g, \omega_I, I)$. This still leaves $\mu_I : \mu^{-1}(0)_{\mathbb{C}} \to \mathfrak{g}^*$, the moment map for $G \circlearrowright (\mu^{-1}(0), g, \omega_I, I)$ which we can use to do a Kähler reduction to find

$$M///G = \mu_{\mathbb{C}}^{-1}(0)//G = \mu_{\mathbb{C}}^{-1}(0) \cap \mu_I^{-1}(0)/G = \mu^{-1}(0)/G. \tag{3.13}$$

This is called the HK reduction as we get the same $M///G$ complete with HK structures $\bar{I}, \bar{J}, \bar{K}$ regardless of which complex structre is singled out when doing the reduction. As it inherits all three complex structures $M///G$ is a HK manifold.

This also has a holomorphic symplectic interpretation with $\omega_{\mathbb{C}} = \omega_J + I\omega_K$ a holomorphic symplectic structure on $(M, g, \omega_I, I)$ with $\mu_{\mathbb{C}}$ the holomorphic moment map of the extended $G_{\mathbb{C}}$ action on $(M, I, \omega_{\mathbb{C}})$. Then the holomorphic symplectic quotient is

$$\text{``}M//G_{\mathbb{C}}\text{''} = \mu_{\mathbb{C}}^{-1}(0)/G_{\mathbb{C}} = \mu^{-1}(0)/G. \tag{3.14}$$

The dimension of the quotient is

$$\dim(M///G) = \dim M - 4\dim G. \tag{3.15}$$

There is actually a whole $S^2$ of complex structures rather than just three since $aI + bJ + cK$ is a complex structure when $(a, b, c) \in S^2 \subset \mathbb{R}^3$. The quotient story holds for any of these complex structures and is related to the twistor space of $M$.

**Example 3.5** (From [5]). Note that this needs to be rechecked as it looks like I am secretly using a different convention to Hitchin. I believe that the detials given here are self consistent but the moment maps do not agree exactly with those in [5].

Consider $U(1) \circlearrowright V \oplus V^*$, where $V$ is a Hermitean vector space and $V^*$ is its dual. There is a natural hyperkähler triple on $V \oplus V^*$ given by

$$I : (\partial_z, \partial_w) \to i(\partial_z, \partial_w), \quad J : (\partial_z, \partial_w) \to (i\partial_{\bar{w}}, -i\partial_{\bar{z}}), \quad K : (A, B) \to (-\partial_{\bar{w}}, \partial_{\bar{z}}). \tag{3.16}$$

Exercise to the reader, check that $JK(\partial_z, \partial_w) = I(\partial_z, \partial_w)$. The $U(1)$ action is given by $u \in U(1)$

$$u \cdot (z, w) = (uz, u^{-1}w). \tag{3.17}$$

We can think of $V = \mathbb{C}^n$, then the $n = 2$ case gives the Eguchi-Hansen space with its familiar hyperkähler metric.

The complex moment map for $I$ is
$$\mu_I(z, w) = \|z\|^2 - \|w\|^2, \tag{3.18}$$

and the holomorphic symplectic moment map is

$$\mu_{\mathbb{C}}(z, w) = \mu_J(z, w) + I\mu_K(z, w) = w(z). \tag{3.19}$$

To prove this is the case consider that

$$\omega_I = \frac{i}{2} \sum_{i=1}^{n} \left( dz_i \wedge d\bar{z}_i + dw_i \wedge d\bar{w}_i \right), \tag{3.20}$$

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and the vector field associated with a lie algebra element, e.g. an infinitesimal rotation is

$$X_u = i \sum_{i=1}^{n} \left( z_i \frac{\partial}{\partial z_i} - \bar{z}_i \frac{\partial}{\partial \bar{z}_i} - w_i \frac{\partial}{\partial w_i} + \bar{w}_i \frac{\partial}{\partial \bar{w}_i} \right) \tag{3.21}$$

computing the moment map via

$$d\langle \mu_I(z, wB), u \rangle = i_{X_u} \omega_I, \tag{3.22}$$

gives

$$i_{X_u} \omega_I = -\frac{1}{2} d \left( \|z\|^2 - \|w\|^2 \right) \tag{3.23}$$

so the moment map is

$$\mu_I(z, w) = -\frac{1}{2} \left( \|z\|^2 - \|w\|^2 \right). \tag{3.24}$$

We can compute the other Kähler forms using

$$\omega(U, V) = g(JU, V), \qquad \omega(U, V) = g(KU, V) \tag{3.25}$$

to give

$$\omega_J = \frac{i}{2} \sum_{i=1}^{n} \left( d\bar{w}_i \wedge d\bar{z}_i - d\bar{w}_i \wedge dz_i \right), \tag{3.26}$$

$$\omega_K = \frac{1}{2} \sum_{i=1}^{n} \left( d\bar{w}_i \wedge d\bar{z}_i + d\bar{w}_i \wedge dz_i \right) \tag{3.27}$$

Exercise to the reader check that these are correct. Hint: the conventions here are that $\omega(U, V) = i_V i_U \omega$.
Then we use $\omega_{\mathbb{C}} = \omega_J + i\omega_K = -i \sum_{i=1}^{n} d\bar{z}_i \wedge d\bar{w}_i$ to compute

$$\begin{aligned} i_{X_u} \omega_{\mathbb{C}} &= i \sum_{i=1}^{n} \left( i\bar{w}_i d\bar{z}_i + i\bar{z}_i d\bar{w}_i \right) \\ &= -d \sum_{i=1}^{n} \left( \bar{w}_i \bar{z}_i \right) = d \left( -\bar{w} \left( \bar{z} \right) \right). \end{aligned} \tag{3.28}$$

Thus the two moment maps are

$$\mu_I(z, w) = -\frac{1}{2} \left( \|z\|^2 - \|w\|^2 \right), \qquad \mu_{\mathbb{C}}(z, w) = -\bar{w} \left( \bar{z} \right). \tag{3.29}$$

This does not quite agree with the details in [5] presumably due to some convention differences. I need to check this.

Now we can pick a regular point of $\mu$, e.g. $\zeta = (1, 0, 0)$, and compute the quotient. Making use of the holomorphic symplectic version of the quotient this is

$$\mu_{\mathbb{C}}^{-1}(0,0)/U(1)_{\mathbb{C}} = \{(z, w) \in \mathbb{C}^n \oplus (\mathbb{C}^n)^* \, | \, z \neq 0, \; \bar{w} \left( \bar{z} \right) = 0\}/\mathbb{C}^*. \tag{3.30}$$

The $z \neq 0$ condition is because this is a fixed point of the $\mathbb{C}^*$ action so needs to be excluded to give the semistable points. How do we interpret what this space is?

## 4  Week 4: 29/06/2022

## A  A sketch of the Nahm transform

I need to check that the conventions here match those in [1].

### A.1  Monopole to Nahm

In case we do not cover anything about the Nahm transform I thought that it was worth giving a brief sketch of how the Nahm transform relates a monopole $(\Phi, A)$ to Nahm matrices $(A_0, \vec{A})$. This sketch follows the discussion in [6], [7] also has a nice discussion including explicitly carrying out the Nahm transform for a charge 1 monopole. Consider a Dirac spinor $\Psi(x)$ transforming in the fundamental representation of $SU(2)$ coupled to the charge $N$ monopole $(\Phi, A)$. Write the spinor as

$$\Psi(x) = \begin{pmatrix} \Psi^- \\ \Psi^+ \end{pmatrix}, \tag{A.1}$$

and consider the Dirac equation

$$\begin{pmatrix} 0 & i\left(\vec{\tau} \cdot \vec{D} - i\Phi - s\right) \\ i\left(\vec{\tau} \cdot \vec{D} + i\Phi + s\right) & 0 \end{pmatrix} \begin{pmatrix} \Psi^- \\ \Psi^+ \end{pmatrix} = 0. \tag{A.2}$$

With $\vec{\tau}$ the vector of Pauli matrices, $s$ a constant real parameter, and $D_A = d + \rho(A)\cdot$ the gauge covariant derivative in the representation $\rho$. This reduces to the two equations

$$D\Psi^- = 0 \qquad D^\dagger \Psi^+ = 0, \tag{A.3}$$

with

$$D = i\left(\vec{\tau} \cdot \vec{D} + i\Phi + s\right) \qquad D^\dagger = i\left(\vec{\tau} \cdot \vec{D} - i\Phi - s\right). \tag{A.4}$$

There are two vector spaces of $L^2$ normalisable solutions given by the kernels $\ker D$ and $\ker D^\dagger$. These vector spaces being non-empty depends on the asymptotics of $i\Phi + s$ which has eigenvalues $1 + s, -1 + s$. For solutions to decay in all directions, e.g. to be $L^2$, these need to have opposite signs[8] Thus $s \in [-1, 1]$. Can show that $DD^\dagger \geq 0$ and thus $D$ is surjective and $\ker D^\dagger = \emptyset$, then the Index theorem for $s \in [-1, 1]$ gives

$$\text{Ind}D = \dim\ker D = N. \tag{A.5}$$

The orthonormal basis for $\ker D$ is $\{\Psi^0 | 1 \leq a \leq N\}$ e.g.

$$\int \Psi_a^{0\dagger}(x)\Psi_b^0 d^3x = \delta_{ab}. \tag{A.6}$$

The three Nahm matrices are constructed from the zero modes as

$$(T_j)_{ab} = -i \int x^j \Psi_a^{0\dagger}(x)\Psi_b^0(x)d^3x \tag{A.7}$$

with $j = 1, 2, 3$. The zero modes depend on $s$ and are chosen such that

$$\int x\Psi_a^{0\dagger}(x)\frac{\partial}{\partial s}\Psi_b^0(x)d^3x = 0, \tag{A.8}$$

this would be the connection piece $A_0$ which can be gauged to zero in $1D$.

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[8]May need to give more details for why this is true.

## A.2 Nahm to Monopole

The inverse Nahm transform works in essentially the same way. Gauge $A_0$ to be zero so that the Nahm data is a triple of $N \times N$ matrices $T_j(s)$ with $s \in [-1, 1]$. There are two $1D$ Weyl equations

$$Dv^- = \left( \mathbb{I}_{2N} \frac{d}{ds} + iT_j \otimes \tau_j - \mathbb{I}_N \otimes x^j \tau_j \right) v^-(s) = 0, \tag{A.9}$$

$$D^\dagger v^+ = \left( -\mathbb{I}_{2N} \frac{d}{ds} + iT_j \otimes \tau_j - \mathbb{I}_N \otimes x^j \tau_j \right) v^+(s) = 0, \tag{A.10}$$

with $\vec{x}$ treated as a parameter. Since $DD^\dagger \geq 0$ the second equation has no solutions. Next we need to assume that the $T_j(s)$ have first order poles at $s = \pm 1$ with the matrix residues forming a $N$ dimensional representation of $\mathfrak{su}(N)$. Thus $Dv^- = 0$ has two $L^2$ solutions with orthonormal basis of $\ker D$ $v_a(s)$ $a = 1, 2$ such that

$$\int_{-1}^{1} v_a^\dagger v_b \, ds = \delta_{ab}. \tag{A.11}$$

Since the $v_a$ vary smoothly with $\vec{x}$ we can use them to define $\Phi$ and $A$ for a charge $N$ monopole as

$$(\Phi(x))_{ab} = i \int_{-1}^{1} s v_a^\dagger v_b \, ds, \tag{A.12}$$

$$(A_j(x))_{ab} = \int_{-1}^{1} v_a^\dagger \frac{\partial}{\partial x^j} v_b \, ds. \tag{A.13}$$

**Example A.1.** Consider the case of $N = 1$ where the Nahm data is $T_j = ic_j$ for $c_j$ a constant real vector. The $1D$ representation of $\mathfrak{su}(2)$ is the trivial representation so has no poles at $s = \pm 1$. Thus $c_j$ corresponds to translations in $\mathbb{R}^3$. Consider the centred $N = 1$ monopole with $c_j = 0$, then

$$Dv(s) = \left( \frac{d}{ds} - \vec{\tau} \cdot \vec{x} \right) v(s) = 0. \tag{A.14}$$

This can be integrated to give

$$v(s) = \exp\left( s\vec{\tau} \cdot \vec{x} \right) v(0), \tag{A.15}$$

and the two independent orthonormal solutions are

$$v_1(s) = \sqrt{\frac{r}{\sinh 2r}} \left( \cosh sr + \sinh sr \hat{x} \cdot \vec{\tau} \right) \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \tag{A.16}$$

$$v_2(s) = \sqrt{\frac{r}{\sinh 2r}} \left( \cosh sr + \sinh sr \hat{x} \cdot \vec{\tau} \right) \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{A.17}$$

The orthogonality condition is

$$\int_{-1}^{1} v_1^\dagger v_2 \, ds = 0. \tag{A.18}$$

Constructing the Higgs field gives

$$\Phi_{ab} = i \frac{r}{\sinh 2r} (\hat{x} \cdot \vec{\tau})_{ab} \int_{-1}^{1} 2s \cosh sr \sinh sr \, ds$$

$$= i \left( \coth 2r - \frac{1}{2r} \right) (\hat{x} \cdot \vec{\tau})_{ab}$$

the Higgs field for the BPS monopole. The connection is recovered analogously.

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