Basic idea: if a small change in an MPS is to be computed (e.g. during variational optimization or time-evolution with a small time step), this change lives in the 'tangent space' of the manifold defined by the MPS. Thus, construct a projector onto the tangent space, and implement gauge fixing conditions to remove redundancy due to gauge degrees of freedom. [Haegeman2011]

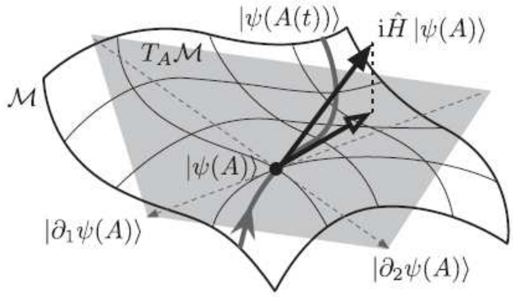
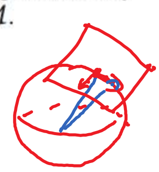


FIG. 1. A sketch of the manifold $\mathcal{M} = \mathcal{M}_{\text{uMPS}}$ (wire frame) embedded in state space. The tangent plane $T_A\mathcal{M}$ to $\mathcal{M}$ (rotated gray square) in a uMPS $|\psi(A)\rangle$ (black dot) is spanned by generally nonorthogonal coordinate axes $|\partial_1\psi(A)\rangle$ and $|\partial_2(A)\rangle$ (dotted lines). The direction $i\hat{H}|\psi(A)\rangle$ of time evolution (arrow with solid head) is best approximated by its orthogonal projection into the tangent plane (arrow with open head). The optimal path $|\psi(A(t))\rangle$ (gray curve) follows the vector field generated by these orthogonally projected vectors throughout $\mathcal{M}$.



This very fundamental and general idea has been elaborated in a series of publications.

[Haegeman2013] Detailed exposition of (improved version of) algorithm.

[Haegeman2014a] Mathematical foundations of tangent space approach in language of diff. geometry. (For a gentle introduction to diff. geometry, see Altland & von Delft, chapters V4, V5.)

[Haegeman2016] Unifying time evolution and optimization within tangent space approach.

[Zauner-Stauber2018] Variational ground state optimization for uniform MPS (for infinite systems).

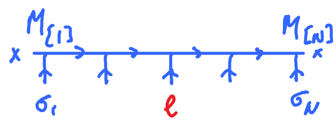
[Vanderstraeten2019] Review-style lecture notes on tangent space methods for uniform MPS.

This lecture follows [Haegeman2016], formulated for finite MPS with open boundary conditions.

1. MPS and canonical forms (reminder)

Consider N-site MPS with open boundary conditions:

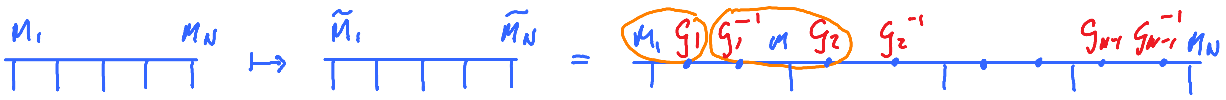
$$|\psi[M]\rangle = |\vec{\sigma}_N\rangle M^{\sigma_1}_{[1]} M^{\sigma_2}_{[2]} \cdots M^{\sigma_N}_{[N]} \qquad (1)$$



where $M^{\sigma_\ell}_{[\ell]}$ is matrix with elements $M^{\alpha\sigma_\ell}_{[\ell]\beta}$, of dimension $D_{\ell-1} \times D_\ell$, with $D_0 = D_N = 1$

shorthand: $M \equiv (M_{[1]}, \dots, M_{[N]}) \in \mathbb{M}$ space of tensors with specified dimensions

Gauge freedom: $|\psi[M]\rangle$ is unchanged under 'gauge transformation' on bond indices:

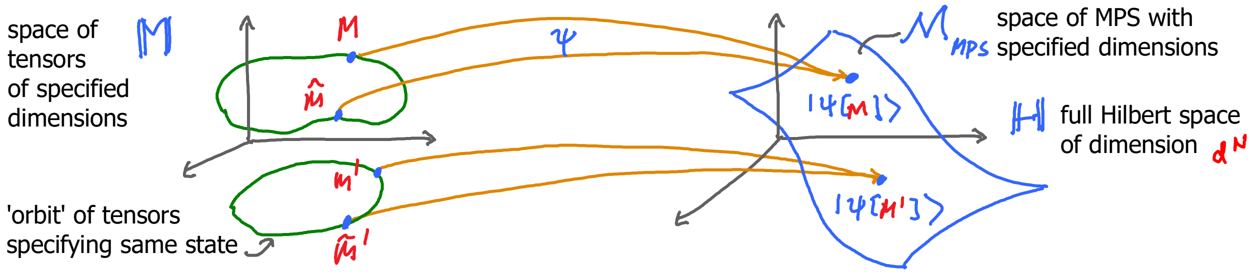


(2)

$$M^{\sigma_\ell}_{[\ell]} \mapsto \tilde{M}^{\sigma_\ell}_{[\ell]} \equiv G^{-1}_{[\ell-1]} M^{\sigma_\ell}_{[\ell]} G_{[\ell]} , \qquad G_{[0]} = G_{[N]} = 1 \qquad (3)$$

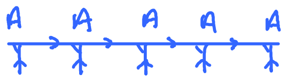
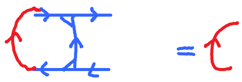
with $G_{[\ell]} \in GL(D_\ell, \mathbb{C})$ group of general complex linear transformation in D_ℓ dimensions

space of MPS with

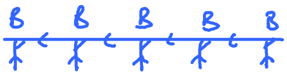
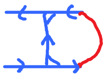


Note: $\mathbb{H}$ and $\mathbb{M}$ are vector spaces, but $\mathcal{M}_{MPS}$ is not, since sum of two MPS with same bond dimensions in general is an MPS with larger bond dimensions. $\mathcal{M}_{MPS}$ is a differential manifold, since it depends smoothly on the tensors in $\mathbb{M}$.

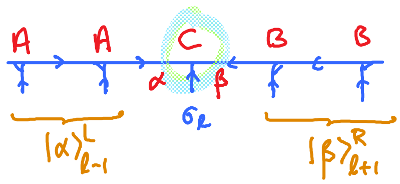
Gauge freedom can be exploited to bring MPS into left-, right-, bond- or site-canonical form:

<u>Left-canonical:</u> $|\psi[M]\rangle =$  with  (4)

Gauge can be fixed uniquely by requiring $A^\dagger_\sigma A^\sigma = \mathbb{1}$ and $A^\sigma A^\dagger_\sigma = \text{diagonal} \ \forall A_{[\ell]}$

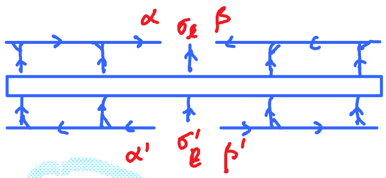
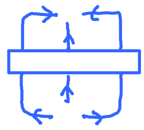
<u>Right-canoncial:</u> $|\psi[M]\rangle =$  with  $= \mathbb{1}$ (5)

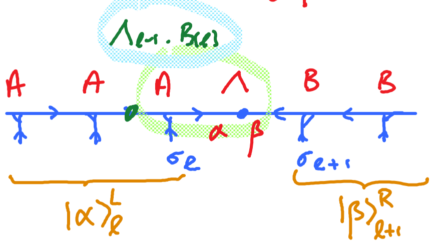
Gauge can be fixed uniquely by requiring $B^\sigma B^\dagger_\sigma = \mathbb{1}$ and $B^\dagger_\sigma B^\sigma = \text{diagonal}. \ \forall B_{[\ell]}$

<u>Site-canonical:</u> $|\psi[M]\rangle =$  $= |\beta\rangle^R_{\ell+1} |\sigma_\ell\rangle |\alpha\rangle^L_{\ell-1} C^{\alpha\sigma_\ell\beta}_{[\ell]}$ (6)

Here $|\alpha\rangle^L_{\ell-1}$ and $|\beta\rangle^R_{\ell+1}$ are orthonormal basis for subspaces representing left- and right parts of chain.

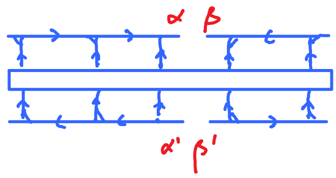
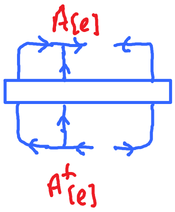
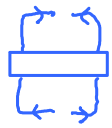
Hamiltonian matrix elements:

${}^L_{\ell-1}\langle\alpha'| \langle\sigma'_\ell| {}^R_{\ell+1}\langle\beta'| \hat H |\beta\rangle^R_{\ell+1} |\sigma_\ell\rangle |\alpha\rangle^L_{\ell-1} =$  $=$  $H_{[\ell]}$ (7)

<u>Bond-canonical:</u> $|\psi[M]\rangle =$  $= |\beta\rangle^R_{\ell+1} |\alpha\rangle^L_\ell \Lambda^{\alpha\beta}_{[\ell]}$

related to site-canonical form by $C_{[\ell]} = A_{[\ell]}\Lambda_{[\ell]} = \Lambda_{[\ell-1]} B_{[\ell]}$

Hamiltonian matrix elements:

${}^L_\ell\langle\alpha'| {}^R_{\ell+1}\langle\beta'| \hat H |\beta\rangle^R_{\ell+1} |\alpha\rangle^L_\ell =$  $=$  $\equiv$  $K_{[\ell]}$ (12)

2. Tangent space

Time-dependent Schrödinger equation: $$-i\frac{d}{dt}|\psi(t)\rangle = \hat{H}|\psi(t)\rangle \qquad (1)$$

General solution is (t-dependent) vector in full many-body Hilbert space, $\mathbb{H}$, of dimension d^N.

Goal: find (approximate) solution as (t-dependent) point in space of MPS with tensors of specified dimensions:

$$|\psi[M(t)]\rangle = M_{[1]}(t)\, \cdots\, M_{[2]}(t)\, \cdots\, M_{[N]}(t) \in \mathcal{M}_{MPS} \qquad (2)$$

Then $$\frac{d}{dt}|\psi[M(t)]\rangle = \sum_{\ell=1}^{N} M_{[1]} \cdots M_{[\ell-1]}\, \dot{M}_{[\ell]}\, M_{[\ell+1]} \cdots M_{[N]} \equiv |\Phi[\dot{M}]\rangle_{M(t)} \qquad (3)$$

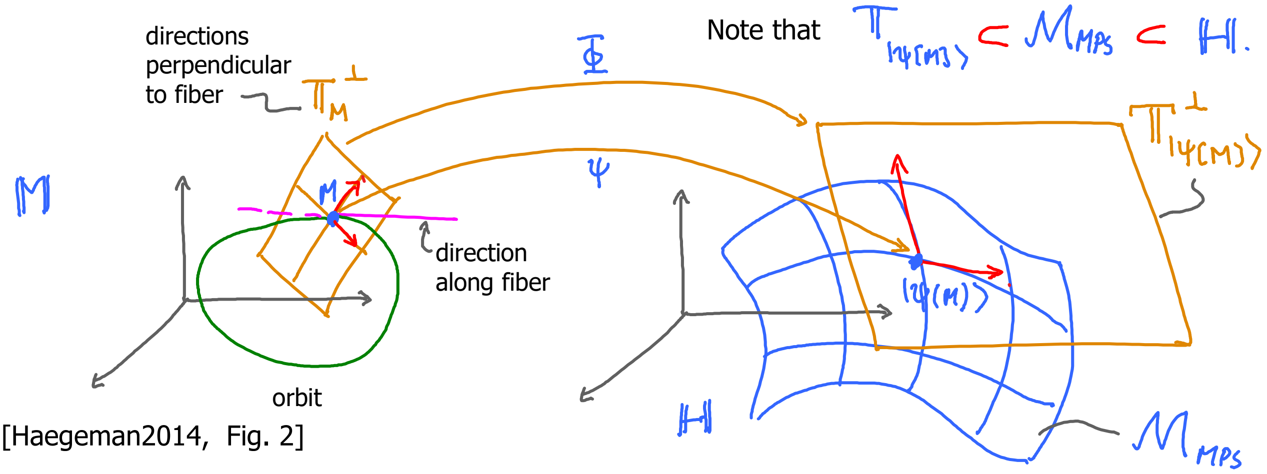
Here we have introduced the general notation

$$|\Phi[T]\rangle_M = \sum_{\ell=1}^{N} M_{[1]} \cdots M_{[\ell-1]}\, T_{[\ell]}\, M_{[\ell+1]} \cdots M_{[N]} \equiv |\partial_j \psi[M]\rangle T^j \qquad (4)$$

shorthand: $T \equiv (T_{[1]}, \dots, T_{[N]}) \in \mathbb{M}$ with composite index $j = (\ell, \alpha, \sigma, \beta)$

For a given set of tensors $M \in \mathbb{M}$, specifying a given MPS $|\psi[M]\rangle \in \mathcal{M}_{MPS}$, the space of all states $|\Phi[T]\rangle_M$ with $T \in \mathbb{M}$, is a vector space (since $|\Phi[T]\rangle$ is linear in T). It is called the 'tangent space', $\mathbb{T}_{|\psi(M)\rangle}$, associated with the 'base point' $|\psi(M)\rangle$ in the manifold $\mathcal{M}_{MPS}$.

Note that $\mathbb{T}_{|\psi[M]\rangle} \subset \mathcal{M}_{MPS} \subset \mathbb{H}$.



[Haegeman2014, Fig. 2]

Remark: the gauge freedom available for describing $|\psi[M]\rangle$ implies a related gauge freedom available for constructing its tangent space. We obtain a unique construction via the following criteria:

(i) We pick a representative M along each ~~fiber~~ orbit. (fix gauge for $|\psi[M]\rangle$), e.g. by picking one of the canonical forms.

(ii) Changes of M pointing 'along an orbit' amount to gauge transformations and do not change $|\psi[M]\rangle$. To construct tangent space $\mathbb{T}_{|\psi[M]\rangle}$, we consider only T's describing changes of M

(ii) Changes of M pointing along an orbit amount to gauge transformations and do not change $|\psi[M]\rangle$. To construct tangent space $\mathbb{T}_{|\psi[M]\rangle}$, we consider only T's describing changes of M orthogonal to such directions.

(iii) Since time evolution is unitary (norm-preserving), $\langle\psi(t)|\psi(t)\rangle = 1$, we consider only T's describing changes of M producing tangent vectors orthogonal to $|\psi[M]\rangle$ itself.

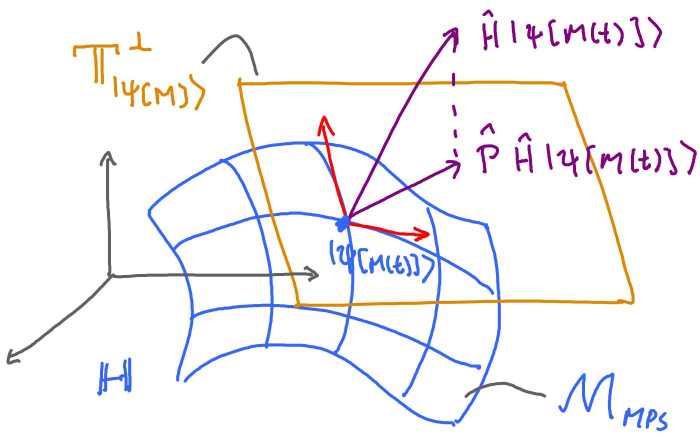
We denote the vector space of T's satisfying these conditions by $\mathbb{T}^{\perp}_{M}$.

Then each $T \in \mathbb{T}^{\perp}_{M}$ uniquely specifies a corresponding tangent vector $|\Phi[T]\rangle_M$ in $\mathbb{T}^{\perp}_{|\psi[M]\rangle}$, the subset of tangent space orthogonal to $|\psi[M]\rangle$ (w.r.t. scalar product in Hilbert space $\mathbb{H}$):

$$\langle\Phi[T]_M|\Psi[M]\rangle = 0 \qquad \forall\ T \in \mathbb{T}^{\perp}_{M} \tag{5}$$

According to (3) and (iii), left-hand side of Schrödinger equation, $-i\frac{d}{dt}|\psi(t)\rangle$, is in $\mathbb{T}^{\perp}_{|\psi[M]\rangle}$.
However, the right side, $\hat{H}|\psi(t)\rangle$, is not. In fact, action of $\hat{H}$ in general produces MPS with larger bond dimensions. Our decision to solve time evolution within $\mathcal{M}_{MPS}$ of specified dimension thus inevitably involves an approximation. The best we can then do is to project $\hat{H}|\psi(t)\rangle$ into orthogonal tangent space $\mathbb{T}^{\perp}_{|\psi[M]\rangle}$, using a projector $\hat{P}_{\mathbb{T}^{\perp}_{|\psi[M(t)]\rangle}}$, and write Schrödinger eq. as

$$-i\frac{d}{dt}|\psi[M(t)]\rangle = \hat{P}_{\mathbb{T}^{\perp}_{|\psi[M(t)]\rangle}}\hat{H}|\psi[M(t)]\rangle \tag{6}$$

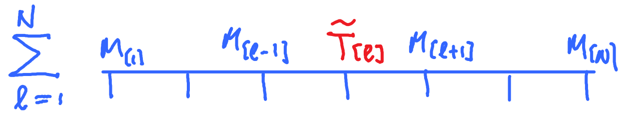


To implement this idea explicitly, we need explicit construction of the projector $\hat{P}$.

'time-dependent variational principle' (TDVP)

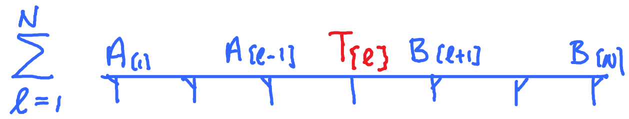
3. Tangent space projector

TS.3

General form of tangent vector: 

(1)

Gauge freedom can be used to bring ℓ-th summand into site-canonical form w.r.t. to site ℓ :

$$|\Phi[T]\rangle_M = $$ 

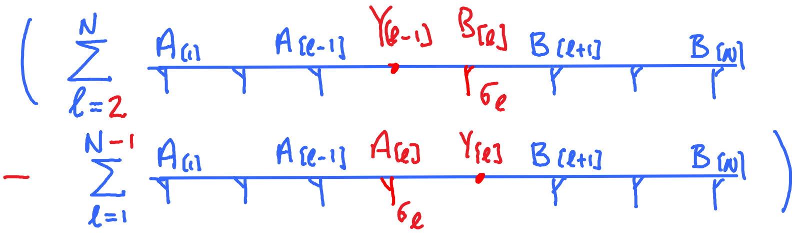
(2)

There is still gauge freedom left: $|\Phi[T]\rangle_M$ does not change under the replacement

$$T_{[\ell]} \longmapsto \tilde{T}_{[\ell]} = T_{[\ell]} + Y_{[\ell-1]} B_{[\ell]} - A_{[\ell]} Y_{[\ell]} , \qquad Y_{[0]} = Y_{[N]} = 0. \tag{3}$$

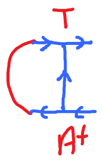
$$A^\dagger \tilde{T} = 0 \qquad A^\dagger (T + YB - AY) = 0$$

with $Y_{[\ell]}$ an arbitrary matrix of dimensions $D_\ell \times D_\ell$

Check: extra terms yield 

(4)

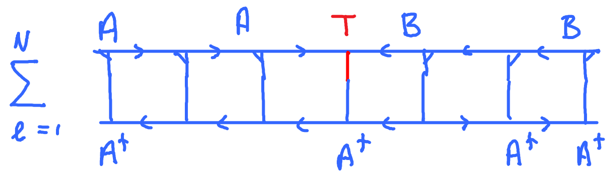
This freedom can be exploited to impose the following '<u>left gauge fixing condition</u>' (LGFC) on $T_{[\ell]}$:

$$A^{\dagger}_{[\ell]\sigma} T^{\sigma}_{[\ell]} = 0 \qquad \forall\, \ell = 1, \dots, N-1$$ 

$= 0$ (5)

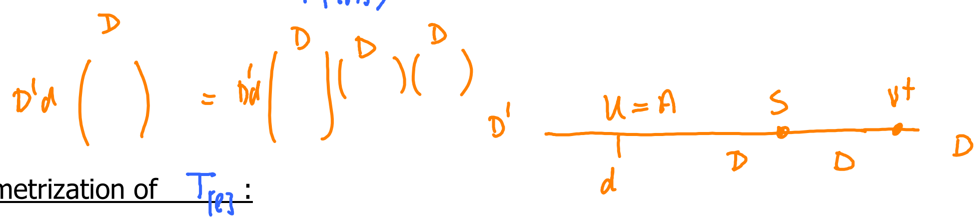
[If T does not satify LGFC, replace it by $\tilde{T}$, with Y chosen such that $\tilde{T}$ does satisfy LGFC.]

The LGFC has two convenient properties. First, it ensures orthogonality of tangent vector to its base point vector:

$$\langle \Psi[M] | \Phi[T] \rangle_M = $$ 

$= 0$ (6)

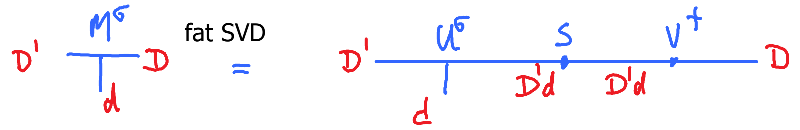
as required by property (iii) of Sec. TS.2. Second, it enables construction of an orthonormal basis for the orthogonal tangent space $\mathbb{T}^{\perp}_{|\Psi[M]\rangle}$. To this end, we adopt a more convenient parameterization of $T_{[\ell]}$.



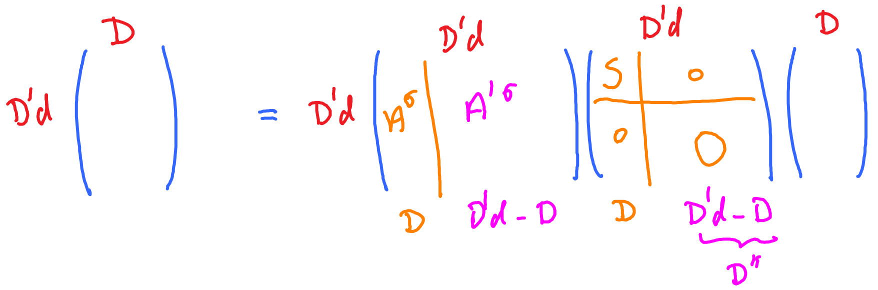
<u>Parametrization of $T_{[\ell]}$:</u>

Recall that each $A^{\sigma}_{[\ell]}$ was obtained by 'thin' SVD of some $M^{\sigma}_{[\ell]}$. Let us consider corresponding 'fat' SVD:

Recall that each $A^\sigma_{[\ell]}$ was obtained by 'thin' SVD of some $M^\sigma_{[\ell]}$. Let us consider corresponding 'fat' SVD:

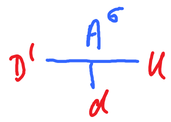


(7)

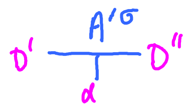


(8)

A^σ is built from the first D columns of the $D'd \times D'd$ unitary matrix U^σ :

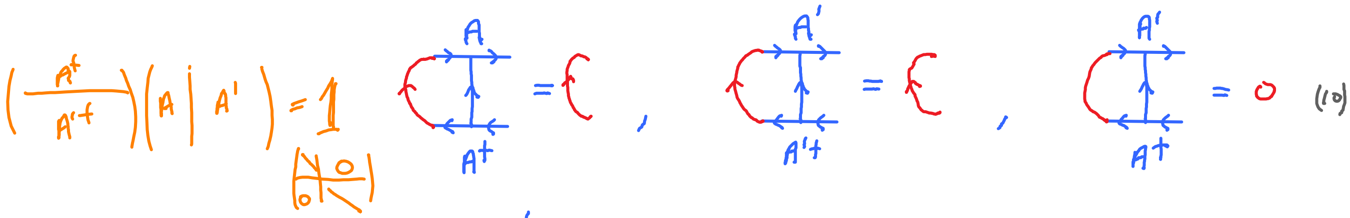


Let A'^σ be similarly built from its remaining $D'' = D'd - D$ columns:



Since U is unitary, the columns of A and A' form orthonormal bases of mutually orthogonal subspaces:

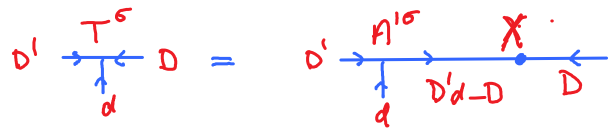
$$U^\dagger_\sigma U^\sigma = \mathbb{1}_{dD' \times dD'} \Rightarrow A^\dagger_\sigma A^\sigma = \mathbb{1}_{D\times D}, \quad A'^\dagger_\sigma A'^\sigma = \mathbb{1}_{D''\times D''}, \quad A^\dagger_\sigma A'^\sigma = 0 \qquad (9)$$



(10)

Exploiting orthogonality of A and A', we can parametrize T in following factorized form

$$T^\sigma_{[\ell]} = A'^{\sigma_\ell}_{[\ell]} X_{[\ell]} ,$$

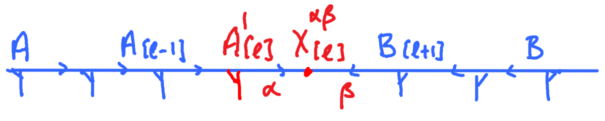


(11)

where $X_{[\ell]}$ is an arbitrary $(D'd - D) \times D$ matrix, and (9,far right) ensures that LGFC (5) holds.

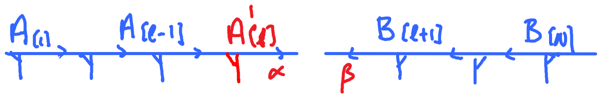
After left-gauge-fixing, tangent vectors have the following general form, parametrized by X :

$$|\Phi[X]\rangle_M \overset{(1),(11)}{=} \sum_{\ell=1}^{N}$$



$$\equiv \sum_{\ell=1}^{N} X^{\alpha\beta}_{[\ell]} |\Phi_{\ell,\alpha\beta}\rangle_M \qquad (12)$$

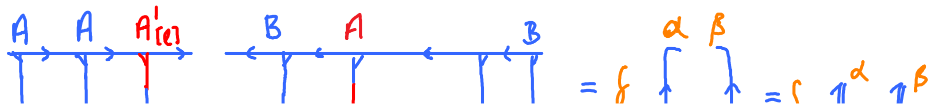
Here the set of states $|\Phi_{\ell,\alpha\beta}\rangle_M \equiv$



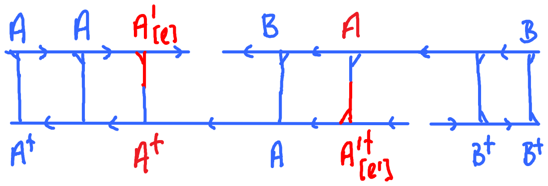
(13)

form an orthonormal basis for the orthogonal tangent space $\mathbb{T}^\perp_{|\psi[M]\rangle}$, since

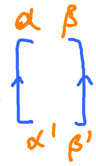
$\langle \Phi_{\ell',\alpha'\beta'} | \Phi_{\ell,\alpha\beta} \rangle =$



$$ {}_M\langle \Phi_{\ell',\alpha'\beta'} | \Phi_{\ell,\alpha\beta} \rangle_M = $$



$$ = \delta_{\ell\ell'} $$



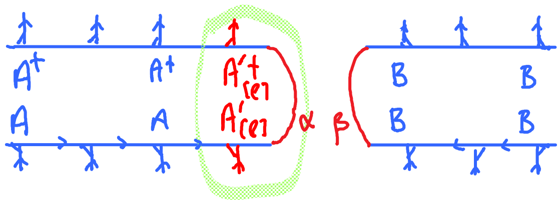
$$ = \delta_{\ell\ell'} \, \mathbb{1}^{\alpha}{}_{\alpha'} \, \mathbb{1}^{\beta}{}_{\beta'} \qquad (14) $$

[(9) ensures that terms with $\ell' \neq \ell$ vanish, and for the $\ell' = \ell$ terms, we can close zipper from left and right.]

Tangent space projector

Tangent space basis yields desired projector onto orthogonal tangent space $\mathbb{T}^{\perp}_{|\psi[M]\rangle}$:

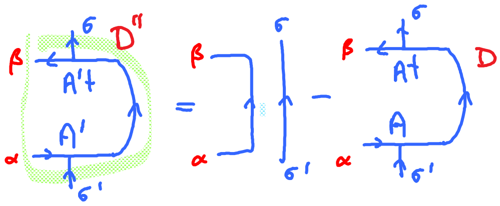
$$ \hat{P}_{\mathbb{T}^{\perp}_{|\psi[M]\rangle}} = \sum_{\ell\alpha\beta} |\Phi_{\ell,\alpha\beta}\rangle\langle\Phi_{\ell,\alpha\beta}| = \sum_{\ell=1}^{N} $$



$$ (15) $$

It is convenient to 'eliminate' the dependence on A' using

$$ A'^{\sigma'} A'^{\dagger}_{\sigma} = \mathbb{1}^{\alpha}_{\beta} \mathbb{1}^{\sigma'}_{\sigma} - A^{\sigma'} A^{\dagger}_{\sigma} \quad , $$

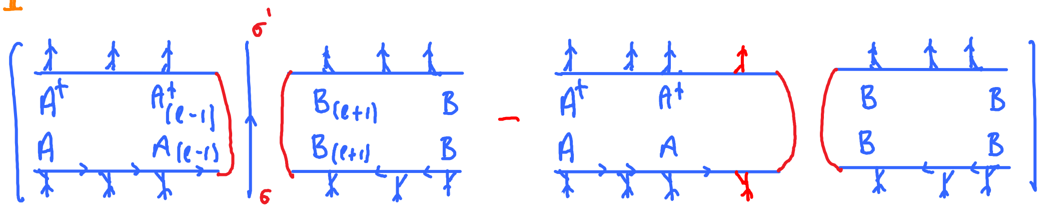


$$ (16) $$

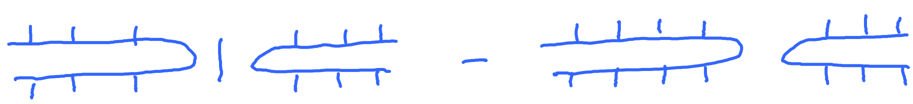
[Check: $\underbrace{A'^{\dagger}_{\sigma'} (A'^{\sigma'}}_{\mathbb{1}} A'^{\dagger}_{\sigma}) \overset{(9)}{=} A'^{\dagger}_{\sigma}$, $A^{\dagger}_{\sigma'} (A'^{\sigma'} A'^{\dagger}_{\sigma}) \overset{(9)}{=} 0$]

Then

$$ \hat{P}_{\mathbb{T}^{\perp}_{|\psi[M]\rangle}} = \sum_{\ell=1}^{N} $$



$$ = \sum_{\ell=1}^{N} $$



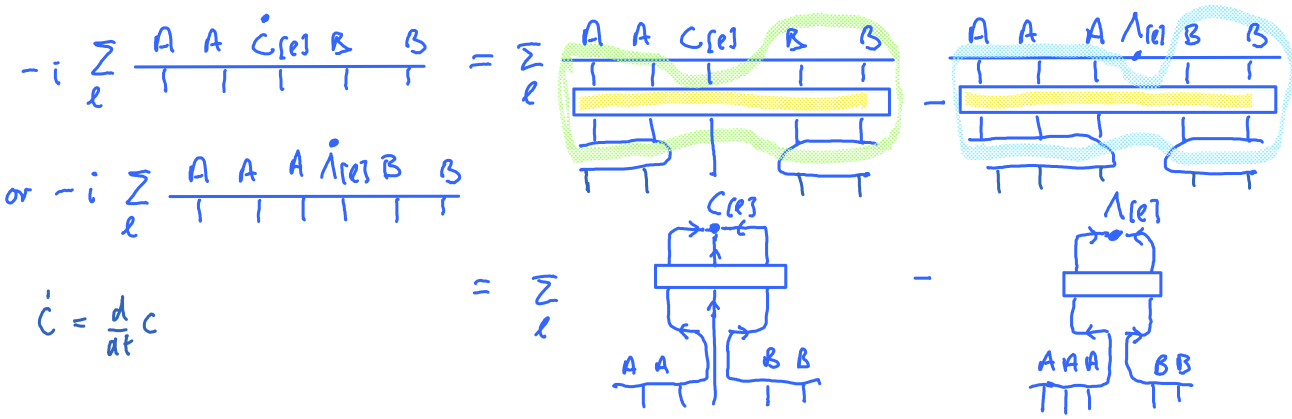
$$ (17) $$

This is our final expression for desired tangent space projector. It is built fully from known tensors!

4. Time evolution

Schrödinger equation now takes the form

$$-i \frac{d}{dt} |\psi[M(t)]\rangle = \hat{P}_{T_{|\psi[M(t)]\rangle}} \hat{H} |\psi[M(t)]\rangle$$



Can be integrated one site at a time:

$$C_{[\ell]}(t \quad) = \qquad C_{[\ell]}(t) \qquad \text{forward in time}$$

$$\Lambda_{[\ell]}(t \quad) = \qquad \Lambda_{[\ell]}(t) \qquad \text{backward in time}$$

Forward sweep, starting from $C_{[1]}(t) B_{[2]}(t) \ldots B_{[N]}(t)$

$$C_{[\ell]}(t)\, B_{[\ell+1]}(t) \xrightarrow{H_{[\ell]}} \underbrace{C_{[\ell]}(t \quad)}\, B_{[\ell+1]}(t)$$

$$= \qquad B_{[\ell+1]}(t)$$

$$\xrightarrow{K_{[\ell]}} A_{[\ell]}(t+\tau) \quad \underbrace{\qquad\qquad}$$

$$A_{[\ell]}(t+\tau) \qquad \text{etc.}$$

until we reach last site, and MPS described by $A_{[1]}(t+\tau) \ldots A_{[N-1]}(t+\tau)\, C_{[N]}(t)$ (13)

2. Turn around: $C_{[N]}(t) \xrightarrow[2(a)]{H_{[N]}} C_{[N]}(t+\tau) \xrightarrow[2(b)]{H_{[N]}} C_{[N]}(t+2\tau)$ (14)

3. Backward sweep, for $\ell = N-1, \ldots, 1$, starting from $A_{[1]}(t+\tau) \ldots A_{[N-1]}(t+\tau)\, C_{[N]}(t+2\tau)$

3. Backward sweep, for $\ell = N-1, \dots, 1$, starting from $A_{[1]}(t+\tau)\dots A_{[N-1]}(t+\tau)\, C_{[N]}(t+2\tau)$

$$A_{[\ell]}(t+\tau)\, C_{[\ell+1]}(t+2\tau) \underset{3(a)}{=} A_{[\ell]}(t+\tau)\, \tilde{\Lambda}_{[\ell]}(t+2\tau)\, B_{[\ell+1]}(t+2\tau) \quad (15)$$

$$\xrightarrow[3(b)]{K_{[\ell]}} \underbrace{A_{[\ell]}(t+\tau)\, \hat{\Lambda}_{[\ell]}(t+\tau)\, B_{[\ell+1]}}_{3(c)}(t+2\tau) \quad (16)$$

$$= C_{[\ell]}(t+\tau)\, B_{[\ell]}(t+2\tau) \quad (17)$$

$$\xrightarrow[3(d)]{H_{[\ell]}} C_{[\ell]}(t+2\tau)\, B_{[\ell]}(t+2\tau) \quad (18)$$

until we reach first site, and MPS described by $C_{[1]}(t+2\tau)\, B_{[2]}(t+2\tau)\dots B_{[N]}(t+2\tau)$

The scheme described above involves 'one-site updates'. This has the drawback (as in one-site DMRG), that it is not possible to dynamically exploring different symmetry sectors. To overcome this drawback, a 'two-site update' version of tangent space methods can be set up [Haegemann2016, App. C].

A systematic comparison of various MPS-based time evolution schemes has been performed in [Paeckel2019]. Conclusion: 2-site-update tangent space scheme is most accurate!