Analyzing Quantum Many-Body Systems with ITensor and PastaQ

Matthew Fishman
Center for Computational Quantum Physics (CCQ)
Flatiron Institute, NY
https://mtfishman.github.io/

February 26, 2022

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mtfishman.github.io

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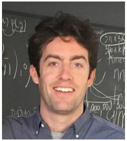

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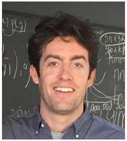

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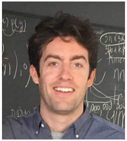

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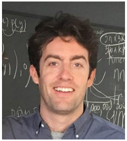

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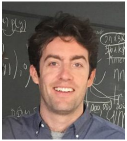

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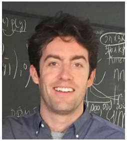

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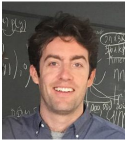

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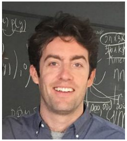

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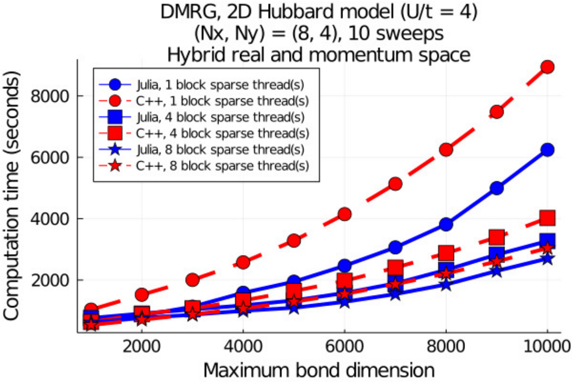

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  - Find out more: github.com/GTorlai/PastaQ.jl

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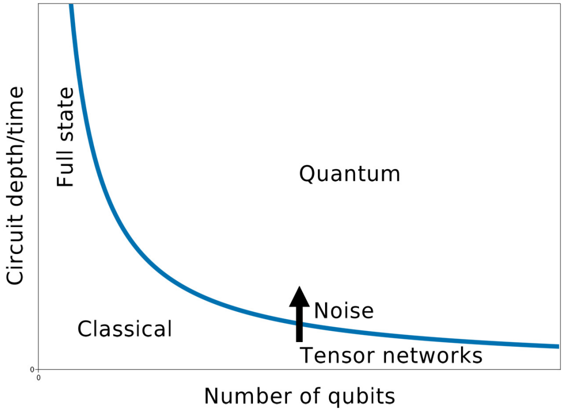
- Tensor networks are a common, general language for reasoning about quantum many-body systems (for example, quantum circuits).

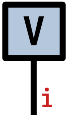
When should I use tensor networks?

- In my opinion, tensor networks are the best general purpose tool we have right now for studying quantum many-body systems (while we wait for a general purpose quantum computer).

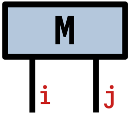


What are tensor networks?

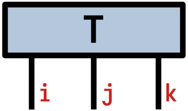
Vector V_i
Order-1 tensor



Matrix M_{ij}
Order-2 tensor



Tensor T_{ijk}
Order-3 tensor



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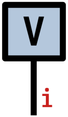

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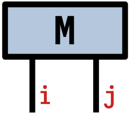

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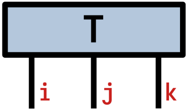
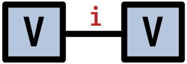
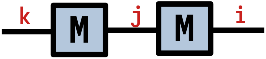


Vector inner product



Matrix-vector multiplication

Matrix-matrix multiplication



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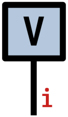

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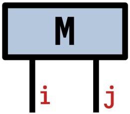

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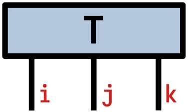

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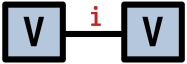

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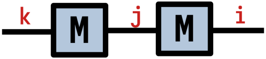
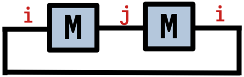
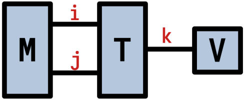


Trace of matrix-matrix multiplication



General tensor network



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3. Type the following commands:

```
julia> using Pkg

julia> Pkg.add("ITensors")
[...]

julia> Pkg.add("PastaQ")
[...]
```

How do I install ITensor/PastaQ?

Now you can use ITensors and PastaQ:

```
julia> using ITensors

julia> i = Index(2);

julia> A = ITensor(i);

julia> using PastaQ

julia> gates = [("X", 1), ("CX", (1, 3))];

julia>   = runcircuit(gates);
```

Tutorial: One-site state basics

```julia
using ITensors

i = Index(2)


```

Load ITensor

2-dimensional labeled Hilbert space (dim=2|id=510)

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using ITensors

i = Index(2)


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```julia
Zp = ITensor(i)
Zp[i=>1] = 1

Zp = ITensor([1, 0], i)
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$$|Z+\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Construct from a Vector

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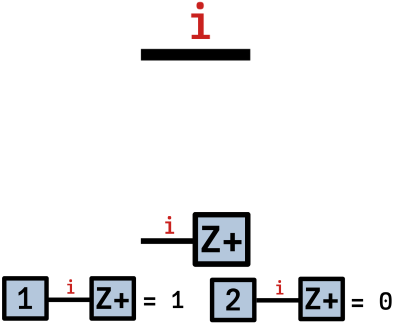

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Zm = ITensor([0, 1], i)
Xp = ITensor([1, 1]/√2, i)
Xm = ITensor([1, -1]/√2, i)
```

$$|Z+\rangle = \begin{bmatrix}1\\0\end{bmatrix}, \; |Z-\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

$$|X+\rangle = \begin{bmatrix}1\\1\end{bmatrix} / \sqrt{2}, \; |X-\rangle = \begin{bmatrix}1\\-1\end{bmatrix} / \sqrt{2}$$

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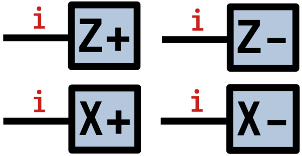

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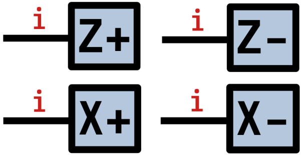


```
(Zp + Zm)/√2
dag(Zp) * Xp
(dag(Zp) * Xp)[]
inner(Zp, Xp)
norm(Xp)
```

≈ Xp
≈ ITensor(1/√2)
≈ 1/√2
≈ 1/√2
≈ 1

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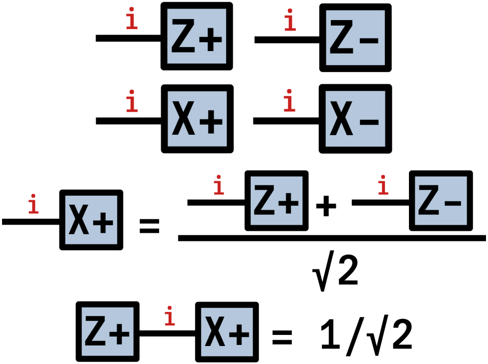
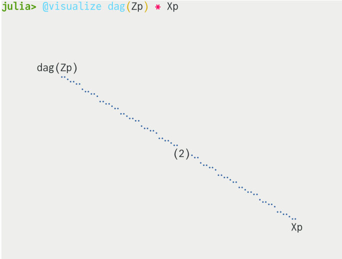
Xm = ITensor([1, -1]/√2, i)
```

```
(Zp + Zm)/√2
dag(Zp) * Xp
(dag(Zp) * Xp)[]
inner(Zp, Xp)
norm(Xp)
```



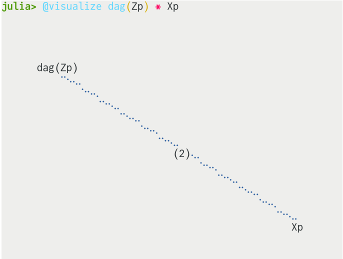
Tutorial: One-site state basics

```julia
using ITensorUnicodePlots

@visualize dag(Zp) * Xp
```

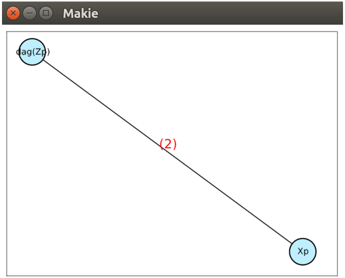


Tutorial: One-site state basics

```julia
using ITensorUnicodePlots

@visualize dag(Zp) * Xp
```




```julia
using ITensorGLMakie

@visualize dag(Zp) * Xp
```



Tutorial: One-site states

```
i = Index(2, "S=1/2")
```

“S=1/2” defines an operator basis

Additionally: “Qubit”, “Qudit”, “Electron”, ...

Tutorial: One-site states

```
i = Index(2, "S=1/2")
```

"S=1/2" defines an operator basis

Additionally:
"Qubit", "Qudit", "Electron", . . .

```
Zp = state("Z+", i)
Zm = state("Z-", i)
Xp = state("X+", i)
Xm = state("X-", i)
```

```
ITensor([1 0], i)
ITensor([0 1], i)
(Zp + Zm)/√2
(Zp - Zm)/√2
```

Tutorial: Custom one-site states

```julia
import ITensors: state


function state(
  ::StateName"iX-",
  ::SiteType"S=1/2"
)
  return [im -im]/√2
end
```

Overload ITensors.jl behavior

Define a state with the name “iX-”

Tutorial: Custom one-site states

```julia
import ITensors: state


function state(
  ::StateName"iX-",
  ::SiteType"S=1/2"
)
  return [im -im]/√2
end
```

Overload ITensors.jl behavior

Define a state with the name “iX-”

```julia
iXm = state("iX-", i)

inner(Zp, iXm)
inner(Zm, iXm)
```

$\approx$ im * Xm

$\approx$ im/$\sqrt{2}$

$\approx$ -im/$\sqrt{2}$

Tutorial: Custom one-site states

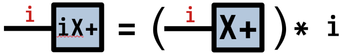
```julia
import ITensors: state


function state(
  ::StateName"iX-",
  ::SiteType"S=1/2"
)
  return [im -im]/√2
end
```

```julia
iXm = state("iX-", i)

inner(Zp, iXm)
inner(Zm, iXm)
```

Overload ITensors.jl behavior

Define a state with the name "iX-"



Tutorial: Priming

```
i = Index(2)
j = Index(2)

i == j
```

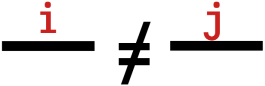
(dim=2|id=837)
(dim=2|id=899)

false

Tutorial: Priming

```
i = Index(2)
j = Index(2)

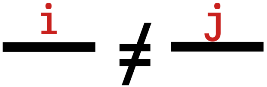
i == j
```



Tutorial: Priming

```
i = Index(2)
j = Index(2)

i == j
```




```
i = Index(2)

prime(i)
i'
i == i'
noprime(i')
```

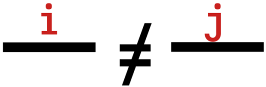
(dim=2|id=837)

(dim=2|id=837)'
(dim=2|id=837)'
false
(dim=2|id=837)

Tutorial: Priming

```
i = Index(2)
j = Index(2)

i == j
```




```
i = Index(2)

prime(i)
i'
i == i'
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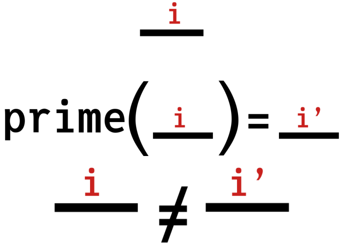


Tutorial: One-site operators

```
Z = ITensor(i', i)
Z[i'=>1, i=>1] = 1
Z[i'=>2, i=>2] = -1
```

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Tutorial: One-site operators

```
Z = ITensor(i', i)
Z[i'=>1, i=>1] = 1
Z[i'=>2, i=>2] = -1
```

Tutorial: One-site operators

```
Z = ITensor(i’, i)
Z[i’=>1, i=>1] = 1
Z[i’=>2, i=>2] = -1
```


```
z = [
  1 0
  0 -1
]

Z = ITensor(z, i’, dag(i))

Z = op("Z", i)
```

Matrix representation Z

Convert to ITensor

Use predefined definition

Tutorial: One-site operators

```
Z = op("Z", i)
X = op("X", i)

Zp = state("Z+", i)
Zm = state("Z-", i)
```

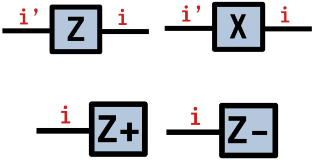
Z
X

|Z+⟩
|Z-⟩

Tutorial: One-site operators

```
Z = op("Z", i)
X = op("X", i)

Zp = state("Z+", i)
Zm = state("Z-", i)
```



Tutorial: One-site operators

```
Z = op("Z", i)
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Zp = state("Z+", i)
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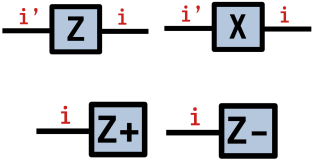
```




```
XZp = X * Zp
XZp == Zm
XZp == Zm'
noprime(XZp) == Zm
```

$X|Z+\rangle = |Z\text{-}\rangle$

false

true

true

Tutorial: One-site operators

```julia
Z = op("Z", i)
X = op("X", i)

Zp = state("Z+", i)
Zm = state("Z-", i)
```

```julia
XZp = X * Zp
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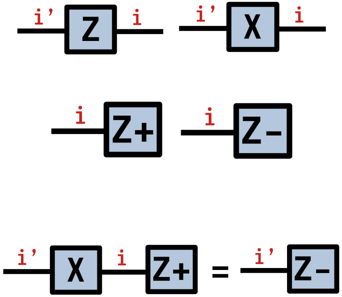


Tutorial: One-site operators

```
XZp = X * Zp

inner(Zm, XZp)

inner(Zm', XZp)
inner(Zp', XZp)
```

$X|Z+\rangle = |Z-\rangle$

error: not a scalar value

≈ 1

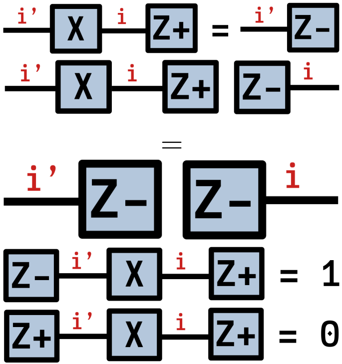
≈ 0

Tutorial: One-site operators

```
XZp = X * Zp

inner(Zm, XZp)

inner(Zm', XZp)
inner(Zp', XZp)
```



Tutorial: One-site operators

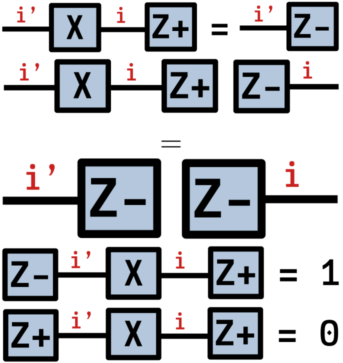
```
XZp = X * Zp

inner(Zm, XZp)

inner(Zm', XZp)
inner(Zp', XZp)
```

```
(dag(Zm)' * X * Zp)[]
inner(Zm', X, Zp)

XZp = apply(X, Zp)
inner(Zm, XZp)
```



≈ 1

≈ 1

$= \text{noprime}(X * Zp)$

≈ 1

Tutorial: One-site operators

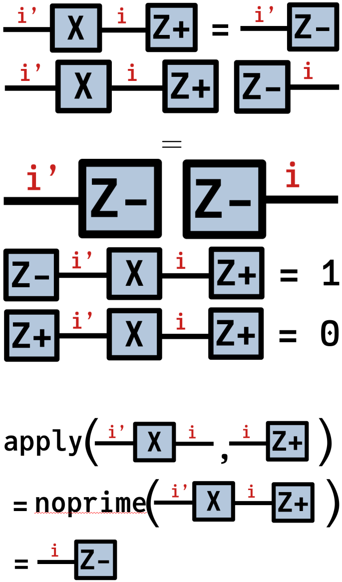
```
XZp = X * Zp

inner(Zm, XZp)

inner(Zm', XZp)
inner(Zp', XZp)
```

```
(dag(Zm)' * X * Zp)[]
inner(Zm', X, Zp)

XZp = apply(X, Zp)
inner(Zm, XZp)
```



Tutorial: Custom one-site operators

```julia
import ITensors: op

function op(
  ::OpName"iX",
  ::SiteType"S=1/2"
)
  return [
    0 im
    im 0
  ]
end
```

Overload ITensors.jl behavior

Tutorial: Custom one-site operators

```julia
import ITensors: op

function op(
  ::OpName"iX",
  ::SiteType"S=1/2"
)
  return [
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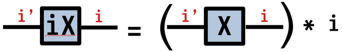
    im 0
  ]
end
```



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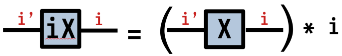
import ITensors: op

function op(
  ::OpName"iX",
  ::SiteType"S=1/2"
)
  return [
    0 im
    im 0
  ]
end
```

```julia
op("iX", i)
```



Tutorial: Custom one-site operators

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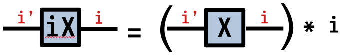



```julia
im * X
```

Tutorial: Two-site states

```
i1 = Index(2, "S=1/2")
i2 = Index(2, "S=1/2")

i1 == i2

ZpZm = ITensor(i1, i2)
ZpZm[i1=>1, i2=>2] = 1
```

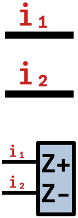
(dim=2|id=505|“S=1/2”)
(dim=2|id=576|“S=1/2”)

false

$|Z+\rangle_1 |Z-\rangle_2 = |Z+Z-\rangle$

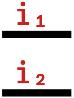
Tutorial: Two-site states

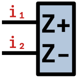
```
i1 = Index(2, "S=1/2")
i2 = Index(2, "S=1/2")

i1 == i2

ZpZm = ITensor(i1, i2)
ZpZm[i1=>1, i2=>2] = 1
```



Tutorial: Two-site states

```julia
i1 = Index(2, "S=1/2")
i2 = Index(2, "S=1/2")

i1 == i2

ZpZm = ITensor(i1, i2)
ZpZm[i1=>1, i2=>2] = 1
```






```julia
Zp1 = state("Z+", i1)
Zp2 = state("Z+", i2)

Zm1 = state("Z-", i1)
Zm2 = state("Z-", i2)

ZpZm = Zp1 * Zm2
ZmZp = Zm1 * Zp2
```

$|\text{Z+}\rangle_1$

$|\text{Z+}\rangle_2$

$|\text{Z-}\rangle_1$

$|\text{Z-}\rangle_2$

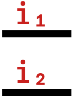
$$|\text{Z+Z-}\rangle = |\text{Z+}\rangle_1 |\text{Z-}\rangle_2$$

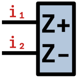
$$|\text{Z-Z+}\rangle = |\text{Z-}\rangle_1 |\text{Z+}\rangle_2$$

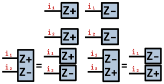
Tutorial: Two-site states

```
i1 = Index(2, "S=1/2")
i2 = Index(2, "S=1/2")

i1 == i2

ZpZm = ITensor(i1, i2)
ZpZm[i1=>1, i2=>2] = 1
```

```
Zp1 = state("Z+", i1)
Zp2 = state("Z+", i2)

Zm1 = state("Z-", i1)
Zm2 = state("Z-", i2)

ZpZm = Zp1 * Zm2
ZmZp = Zm1 * Zp2
```







Tutorial: Two-site states

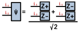
```
 = ITensor(i1, i2)
[i1=>1, i2=>2] = 1/√2
[i1=>2, i2=>1] = 1/√2

 = (Zp1 * Zm2 +
       Zm1 * Zp2)/√2
```

$(|\mathrm{Z+}\rangle|\mathrm{Z-}\rangle + |\mathrm{Z-}\rangle|\mathrm{Z+}\rangle)/\sqrt{2}$

From single-site states

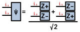
Tutorial: Two-site states

```
  = ITensor(i1, i2)
[i1=>1, i2=>2] = 1/√2
[i1=>2, i2=>1] = 1/√2

  = (Zp1 * Zm2 +
        Zm1 * Zp2)/√2
```



Tutorial: Two-site states

```
 = ITensor(i1, i2)
[i1=>1, i2=>2] = 1/√2
[i1=>2, i2=>1] = 1/√2

 = (Zp1 * Zm2 +
      Zm1 * Zp2)/√2
```




```
inner( ,  )
inner(ZpZm,  )

U, S, V = svd(ZmZp, i1)
s = diag(S)

U, S, V = svd( , i1)
s = diag(S)
```

≈ 1

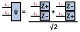
$\approx 1/\sqrt{2}$

$\approx [1,\ 0]$

$\approx [1/\sqrt{2},\ 1/\sqrt{2}]$

Tutorial: Two-site states

```
 = ITensor(i1, i2)
[i1=>1, i2=>2] = 1/√2
[i1=>2, i2=>1] = 1/√2

 = (Zp1 * Zm2 +
      Zm1 * Zp2)/√2
```



```
inner( , )
inner(ZpZm, )

U, S, V = svd(ZmZp, i1)
s = diag(S)

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s = diag(S)
```
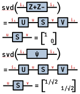



Tutorial: Two-site operators

```
H = ITensor(i1', i2', i1, i2)
H[i1'=>2, i2'=>1,
  i1=>2, i2=>1] = -1
# ...
```

Make a Hamiltonian:
Transverse field Ising
n=2 sites
$H = -\sum_j^{n-1} Z_j Z_{j+1} + h \sum_j^n X_j$

Tutorial: Two-site operators

```
H = ITensor(i1', i2', i1, i2)
H[i1'=>2, i2'=>1,
  i1=>2, i2=>1] = -1
# ...
```

```
Id1 = op("Id", i1)
Z1 = op("Z", i1)
X1 = op("X", i1)
# ...

ZZ = Z1 * Z2
XI = X1 * Id2
IX = Id1 * X2

h = 0.5
H = -ZZ + h * (XI + IX)
```

Make a Hamiltonian:
Transverse field Ising
n=2 sites
$H = -\sum_j^{n-1} Z_j Z_{j+1} + h \sum_j^n X_j$
Alternative:
Build from single-site
operators.
Less error-prone.

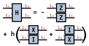
Tutorial: Two-site operators

```
H = ITensor(i1', i2', i1, i2)
H[i1'=>2, i2'=>1,
  i1=>2, i2=>1] = -1
# ...
```

```
Id1 = op("Id", i1)
Z1 = op("Z", i1)
X1 = op("X", i1)
# ...

ZZ = Z1 * Z2
XI = X1 * Id2
IX = Id1 * X2

h = 0.5
H = -ZZ + h * (XI + IX)
```

Make a Hamiltonian:
Transverse field Ising
n=2 sites

$H = -\sum_j^{n-1} Z_j Z_{j+1} + h \sum_j^n X_j$



Tutorial: Two-site operators

```
ZpZp = Zp1 * Zp2



(dag(ZpZp)' * H * ZpZp)[]
inner(ZpZp', H, ZpZp)
inner(ZpZp, apply(H, ZpZp))
```

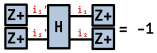
Expectation value:

$\langle \mathrm{H} \rangle = \langle \mathrm{Z+Z+} | \mathrm{H} | \mathrm{Z+Z+} \rangle$

$\approx$ -1

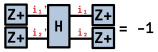
Tutorial: Two-site operators

```
ZpZp = Zp1 * Zp2



(dag(ZpZp)' * H * ZpZp)[]
inner(ZpZp', H, ZpZp)
inner(ZpZp, apply(H, ZpZp))
```



Tutorial: Two-site operators

```
ZpZp = Zp1 * Zp2



(dag(ZpZp)' * H * ZpZp)[]
inner(ZpZp', H, ZpZp)
inner(ZpZp, apply(H, ZpZp))
```

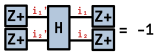


$\approx [-\sqrt{2}, -1, 1, \sqrt{2}]$

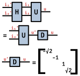
```
D, U = eigen(H)
diag(D)
```

Tutorial: Two-site operators

```
ZpZp = Zp1 * Zp2



(dag(ZpZp)' * H * ZpZp)[]
inner(ZpZp', H, ZpZp)
inner(ZpZp, apply(H, ZpZp))
```




```
D, U = eigen(H)
diag(D)
```



Tutorial: Custom two-site operators

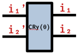
```
import ITensors: op

function op(
  ::OpName"CRy",
  ::SiteType"S=1/2";
  θ
)
  c = cos(θ/2)
  s = sin(θ/2)
  return [
    1 0 0  0
    0 1 0  0
    0 0 c -s
    0 0 s  c
  ]
end
```

Controlled-Ry (CRy) rotation gate

CRy(θ)

Tutorial: Custom two-site operators

```julia
import ITensors: op

function op(
  ::OpName"CRy",
  ::SiteType"S=1/2";
  θ
)
  c = cos(θ/2)
  s = sin(θ/2)
  return [
    1 0 0  0
    0 1 0  0
    0 0 c -s
    0 0 s  c
  ]
end
```



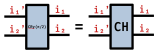
Tutorial: Custom two-site operators

```
CH = op("CRy", i1, i2;
            θ=π/2)
```

Controlled-Hadamard gate
CH = CRy(θ=$\pi/2$)

Tutorial: Custom two-site operators

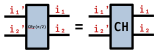
```
CH = op("CRy", i1, i2;
        θ=π/2)
```



Tutorial: Custom two-site operators

```
CH = op("CRy", i1, i2;
          θ=π/2)
```

```
ZpZm = Zp1 * Zm2

CH_Xm = apply(CH, ZpZm)

CH_Xm ≈ Zp1 * Xm2
```



$$|\text{Z+Z-}\rangle = |\text{Z+}\rangle_1 |\text{Z-}\rangle_2$$

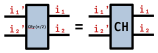
$$\text{CH}|\text{Z+Z-}\rangle = |\text{Z+X-}\rangle$$

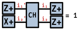
true

Tutorial: Custom two-site operators

```
CH = op("CRy", i1, i2;
            θ=π/2)
```

```
ZpZm = Zp1 * Zm2

CH_Xm = apply(CH, ZpZm)

CH_Xm ≈ Zp1 * Xm2
```





Tutorial: Two-site state optimization

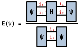
```julia
function E(ψ)
  ψHψ = inner(ψ', H, ψ)
  ψψ = inner(ψ, ψ)
  return ψHψ / ψψ
end
```

Function to minimize: Expectation value of the energy.

$$E(\psi) = \langle\psi|H|\psi\rangle/\langle\psi|\psi\rangle$$

Tutorial: Two-site state optimization

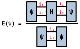
```
function E(ψ)
  ψHψ = inner(ψ', H, ψ)
  ψψ = inner(ψ, ψ)
  return ψHψ / ψψ
end
```



Tutorial: Two-site state optimization

```
function E(ψ)
  ψHψ = inner(ψ', H, ψ)
  ψψ = inner(ψ, ψ)
  return ψHψ / ψψ
end
```

```
function minimize(f, ∂f, x;
  nsteps, γ)
  for n in 1:nsteps
    x = x - γ * ∂f(x)
  end
  return x
end
```



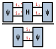
Simple gradient descent. Must provide function f(x) to minimize and ∂f(x), the gradient of f at x. γ is the gradient descent step size.

Tutorial: Two-site state optimization

```
function E(ψ)
  ψHψ = inner(ψ', H, ψ)
  ψψ = inner(ψ, ψ)
  return ψHψ / ψψ
end
```

```
function minimize(f, ∂f, x;
  nsteps, γ)
  for n in 1:nsteps
    x = x - γ * ∂f(x)
  end
  return x
end
```

E(ψ) =



$\min_{\psi} E(\psi)$ $\partial_{\psi} E(\psi)$

Tutorial: Two-site state optimization

```
ψ₀ = (Zp1 * Zm2 +
        Zm1 * Zp2)/√2

E(ψ₀)

using Zygote: gradient
∂E(ψ) = gradient(E, ψ)[1]

norm(∂E(ψ₀))
```

$|\psi_0\rangle = (|Z{+}Z{+}\rangle +$
$|Z{-}Z{-}\rangle)/\sqrt{2}$

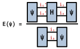
$\approx$ -1

Using Zygote for automatic differentation of the energy.

≈ 2

Tutorial: Two-site state optimization

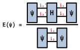
```julia
ψ0 = (Zp1 * Zm2 +
        Zm1 * Zp2)/√2

E(ψ0)

using Zygote: gradient
∂E(ψ) = gradient(E, ψ)[1]

norm(∂E(ψ0))
```



Tutorial: Two-site state optimization

```
ψ₀ = (Zp1 * Zm2 +
        Zm1 * Zp2)/√2

E(ψ₀)

using Zygote: gradient
∂E(ψ) = gradient(E, ψ)[1]

norm(∂E(ψ₀))
```

```
ψ = minimize(E, ∂E, ψ₀;
        nsteps=10, γ=0.1)

E(ψ₀), norm(∂E(ψ₀))
E(ψ), norm(∂E(ψ))

```



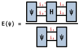
Minimize over ψ:
$E(\psi) = \langle\psi|H|\psi\rangle/\langle\psi|\psi\rangle$

(-1, 2)
(-1.4142131, 0.0010865277)
$\approx$ (-$\sqrt{2}$, 0)

Tutorial: Two-site state optimization

```
ψ₀ = (Zp1 * Zm2 +
        Zm1 * Zp2)/√2

E(ψ₀)

using Zygote: gradient
∂E(ψ) = gradient(E, ψ)[1]

norm(∂E(ψ₀))
```

```
ψ = minimize(E, ∂E, ψ₀;
       nsteps=10, γ=0.1)

E(ψ₀), norm(∂E(ψ₀))
E(ψ), norm(∂E(ψ))

```



$\min_{\psi} E(\psi)$ $\partial_{\psi} E(\psi)$

Tutorial: Two-site circuit optimization

```
# Circuit as a vector of gates:
U(θ, i1, i2) = [
  op("Ry", i1; θ=θ[1]),
  op("Ry", i2; θ=θ[2]),
  op("CX", i1, i2),
  op("Ry", i1; θ=θ[3]),
  op("Ry", i2; θ=θ[4]),
]
```

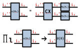
Tutorial: Two-site circuit optimization

```julia
# Circuit as a vector of gates:
U(θ, i1, i2) = [
  op("Ry", i1; θ=θ[1]),
  op("Ry", i2; θ=θ[2]),
  op("CX", i1, i2),
  op("Ry", i1; θ=θ[3]),
  op("Ry", i2; θ=θ[4]),
]
```

```julia
# PastaQ notation:
u(θ, j1, j2) = [
  ("Ry", j1, (; θ=θ[1])),
  ("Ry", j2, (; θ=θ[2])),
  ("CNOT", j1, j2),
  ("Ry", j1, (; θ=θ[3])),
  ("Ry", j2, (; θ=θ[4])),
]
U(θ, i1, i2) =
  buildcircuit(u(θ, 1, 2), [i1, i2])
```

Tutorial: Two-site circuit optimization

```
# Circuit as a vector of gates:
U(θ, i1, i2) = [
  op("Ry", i1; θ=θ[1]),
  op("Ry", i2; θ=θ[2]),
  op("CX", i1, i2),
  op("Ry", i1; θ=θ[3]),
  op("Ry", i2; θ=θ[4]),
]
```



Tutorial: Two-site circuit optimization

[TODO: Add visualization of minimizing <0|UHU|0>]

```
ψ0 = Zp1 * Zp2


function E(θ)
  ψθ = apply(U(θ), ψ0)
  return inner(ψθ', H, ψθ)
end
```

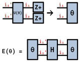
References state:
$|0\rangle = |\mathrm{Z+Z+}\rangle$

Find θ that minimizes:
$E(\theta) = \langle 0|U(\theta)^\dagger \, H \, U(\theta)|0\rangle$
$= \langle \theta|H|\theta\rangle$

Tutorial: Two-site circuit optimization

[TODO: Add visualization of minimizing <0|UHU|0>]

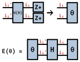
```
ψ₀ = Zp1 * Zp2


function E(θ)
  ψθ = apply(U(θ), ψ₀)
  return inner(ψθ', H, ψθ)
end
```



Tutorial: Two-site circuit optimization

[TODO: Add visualization of minimizing <0|UHU|0>]

```
ψ₀ = Zp1 * Zp2


function E(θ)
  ψθ = apply(U(θ), ψ₀)
  return inner(ψθ', H, ψθ)
end
```




```
θ₀ = [0, 0, 0, 0]
θ = minimize(E, ∂E, θ₀;
          nsteps=40, γ=0.5)

E(θ₀), norm(∂E(θ₀))
E(θ), norm(∂E(θ))

```

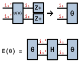
(-1, $\sqrt{3}/2$)
(-1.4142077, 0.0017584116)
$\approx$ (-$\sqrt{2}$, 0)

Tutorial: Two-site circuit optimization

[TODO: Add visualization of minimizing <0|UHU|0>]

```
ψ₀ = Zp1 * Zp2


function E(θ)
  ψθ = apply(U(θ), ψ₀)
  return inner(ψθ', H, ψθ)
end
```

```
θ₀ = [0, 0, 0, 0]
θ = minimize(E, ∂E, θ₀;
        nsteps=40, γ=0.5)

E(θ₀), norm(∂E(θ₀))
E(θ), norm(∂E(θ))

```



$\min_{\theta} E(\theta)$ $\partial_\theta E(\theta)$

Tutorial: Two-site fidelity optimization

[TODO: Add visualization of minimizing <v|U|v0>]

```
ψ0 = Zp1 * Zp2
ψ = (ZpZp + ZmZm) / √2



function F(θ)
  ψθ = apply(U(θ, i1, i2), ψ0)
  return -abs(inner(ψ, ψθ))^2
end
```

Reference state:
$|0\rangle = |Z{+}Z{+}\rangle$

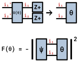
Target state:
$|\psi\rangle = (|Z{+}Z{+}\rangle +$
$|Z{-}Z{-}\rangle)/\sqrt{2}$

Find θ that minimizes:
$F(\theta) = -|\langle\psi|U(\theta)|0\rangle|^2$

Tutorial: Two-site fidelity optimization

[TODO: Add visualization of minimizing <v|U|v0>]

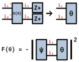
```
ψ₀ = Zp1 * Zp2
ψ = (ZpZp + ZmZm) / √2



function F(θ)
  ψθ = apply(U(θ, i1, i2), ψ₀)
  return -abs(inner(ψ, ψθ))^2
end
```



Tutorial: Two-site fidelity optimization

[TODO: Add visualization of minimizing <v|U|v0>]

```
ψ₀ = Zp1 * Zp2
ψ = (ZpZp + ZmZm) / √2



function F(θ)
  ψ_θ = apply(U(θ, i1, i2), ψ₀)
  return -abs(inner(ψ, ψ_θ))^2
end
```



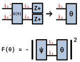

```
θ₀ = [0, 0, 0, 0]
θ = minimize(F, ∂F, θ₀;
        nsteps=50, γ=0.1)

F(θ₀), norm(∂F(θ₀))
F(θ), norm(∂F(θ))
```

$\approx$ (-0.5, 0.5)
$\approx$ (-0.9938992, 0.07786879)
$\approx$ (-1, 0)

Tutorial: Two-site fidelity optimization

[TODO: Add visualization of minimizing <v|U|v0>]

```
ψ₀ = Zp1 * Zp2
ψ = (ZpZp + ZmZm) / √2



function F(θ)
  ψ_θ = apply(U(θ, i1, i2), ψ₀)
  return -abs(inner(ψ, ψ_θ))^2
end
```




```
θ₀ = [0, 0, 0, 0]
θ = minimize(F, ∂F, θ₀;
         nsteps=50, γ=0.1)

F(θ₀), norm(∂F(θ₀))
F(θ), norm(∂F(θ))
```

$\min_\theta F(\theta)$ $\partial_\theta F(\theta)$

Tutorial: n-site states with MPS

[TODO: Add visualization of <Zp| >]

```
n = 30                                  # n−site state
i = [Index(2, "S=1/2")
       for j in 1:n]

Zp = MPS(i, "Z+")                       # |Z+Z+...Z+⟩
Zm = MPS(i, "Z-")                       # |Z−Z−...Z−⟩

  = (Zp + Zm)/√2                        # (|Z+Z+...Z+⟩ +
                                        #  |Z−Z−...Z−⟩)/√2
```

Tutorial: n-site states with MPS

[TODO: Add visualization of <Zp| >]

```
n = 30                                    # n−site state
i = [Index(2, "S=1/2")
       for j in 1:n]

Zp = MPS(i, "Z+")                         # |Z+Z+...Z+⟩
Zm = MPS(i, "Z-")                         # |Z−Z−...Z−⟩

  = (Zp + Zm)/√2                          # (|Z+Z+...Z+⟩ +
                                          #  |Z−Z−...Z−⟩)/√2
```

```
maxlinkdim(Zp)                            # 1 (product state)
maxlinkdim( )                             # 2 (entangled state)
inner(Zp, Zp)                             # ⟨Z+|Z+⟩ ≈ 1
inner(Zm, Zp)                             # ⟨Z−|Z+⟩ ≈ 0
norm( )                                   # (⟨Z+| + ⟨Z−|)(|Z+⟩ + |Z+⟩)/2
                                          #       ≈ 1
```

Tutorial: n-site states with MPS

[TODO: Add visualization of minimizing <psi|H|psi>]

```
j = n ÷ 2
X_j = op("X", i[j])

X_jZp = apply(X_j, Zp)


state = [k == j ? "Z-" : "Z+"
             for k in 1:n]
X_jZp = MPS(i, state)
```

```
# j = n ÷ 2
# X_j

# X_j|Z+Z+...Z+⟩ =
#     |Z+Z+...Z−...Z+⟩

# |Z+Z+...Z−...Z+⟩
```

Tutorial: n-site states with MPS

[TODO: Add visualization of minimizing <psi|H|psi>]

```julia
j = n ÷ 2
X_j = op("X", i[j])

X_jZp = apply(X_j, Zp)


state = [k == j ? "Z-" : "Z+"
         for k in 1:n]
X_jZp = MPS(i, state)
```

```
# j = n ÷ 2
# X_j

# X_j|Z+Z+...Z+⟩ =
#      |Z+Z+...Z−...Z+⟩

# |Z+Z+...Z−...Z+⟩
```

```julia
maxlinkdim(X_jZp)
inner(Zp, X_jZp)
inner(X_jZp, apply(X_j, Zp))
```

```
# 1 (product state)
# ≈ 0
# ≈ 1
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```julia
function ising(n; h)
  H = OpSum()
  for j in 1:(n - 1)
    H -= "Z", j, "Z", j + 1
  end
  for j in 1:n
    H += h, "X", j
  end
  return H
end
```

```
# n sites
# H = -\sum_j^{n-1} Z_j Z_{j+1} + h \sum_j^n X_j
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```julia
function ising(n; h)      # n sites
  H = OpSum()             # H = -∑_j^{n-1} Z_j Z_{j+1} + h ∑_j^n X_j
  for j in 1:(n - 1)
    H -= "Z", j, "Z", j + 1
  end
  for j in 1:n
    H += h, "X", j
  end
  return H
end
```

```julia
h = 0.5
H = MPO(ising(n; h=h), i)
maxlinkdim(H)             # = 3 (local Hamiltonian)
Zp = MPS(i, "Z+")
inner(Zp', H, Zp)         # ⟨Z+Z+...Z+|H|Z+Z+...Z+⟩
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```
ψ0 = MPS(i, "Z+")                          # |0⟩ = |Z+Z+...Z+⟩

ψ = minimize(E, ∂E, ψ0;                    # Minimize over ψ:
        nsteps=50, γ=0.1,                  # ⟨ψ|H|ψ⟩/⟨ψ|ψ⟩
        maxdim=10, cutoff=1e-5)

E_dmrg, ψ_dmrg = dmrg(H, ψ0;               # DMRG solves:
        nsweeps=10,                        # H|ψ⟩ ≈ |ψ⟩
        maxdim=10, cutoff=1e-5)
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```
ψ_0 = MPS(i, "Z+")                          # |0⟩ = |Z+Z+...Z+⟩

ψ = minimize(E, ∂E, ψ_0;                    # Minimize over ψ:
      nsteps=50, γ=0.1,                     # ⟨ψ|H|ψ⟩/⟨ψ|ψ⟩
      maxdim=10, cutoff=1e-5)

E_dmrg, ψ_dmrg = dmrg(H, ψ_0;               # DMRG solves:
      nsweeps=10,                           # H|ψ⟩ ≈ |ψ⟩
      maxdim=10, cutoff=1e-5)
```

```
maxlinkdim(ψ_0)                             # = 1 (product state)
maxlinkdim(ψ)                               # = 3 (entangled state)
maxlinkdim(ψ_dmrg)                          # = 2 (entangled state)
E(ψ_0), norm(∂(ψ_0))                        # ≈ (−29, 5.4772256)
E(ψ), norm(∂E(ψ))                           # ≈ (−31.0317917, 0.06673780)
E(ψ_dmrg), norm(∂E(ψ_dmrg))                 # ≈ (−31.0356110, 0.02413237)
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```
Ry_layer(θ, i) = [op("Ry", i[j]; θ=θ[j]) for j in 1:n]
CX_layer(i) = [op("CX", i[j], i[j+1]) for j in 1:2:(n-1)]
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```
Ry_layer(θ, i) = [op("Ry", i[j]; θ=θ[j]) for j in 1:n]
CX_layer(i) = [op("CX", i[j], i[j+1]) for j in 1:2:(n-1)]
```

```
function U(θ, i; nlayers)
  n = length(i)
  U_θ = Ry_layer(θ[1:n], i)
  for l in 1:(nlayers - 1)
    θ_l = θ[(1:n) .+ l * n]
    U_θ = [U_θ; CX_layer(i)]
    U_θ = [U_θ; Ry_layer(θ_l, i)]
  end
  return U_θ
end
```

```
# U(θ) = Ry_1(θ_1) ... Ry_n(θ_n)
#        CX_{1,2} ... CX_{n-1,n}
#        Ry_1(θ_{n+1}) ... Ry_n(θ_{2n})
#        ...
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```
ψ0 = MPS(i, "Z+")
nlayers = 6
function E(θ)
  ψθ = apply(U(θ, i; nlayers), ψ0)
  return inner(ψθ', H, ψθ)
end

θ0 = zeros(nlayers * n)
θ = minimize(E, ∂E, θ0;
        nsteps=20, γ=0.1)
```

```
# |0⟩ = |Z+Z+...Z+⟩

# Minimize over θ:
# |θ⟩ = U(θ)|0⟩
# E(θ) = ⟨θ|H|θ⟩
```

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```

```julia
maxlinkdim(ψ0)
maxlinkdim(ψθ)
E(θ0), norm(∂E(θ0))
E(θ), norm(∂E(θ))
```

```
# 1 (product state)
# 2 (entangled state)
# (−29, 5.773335)
# (−31.017062, 0.000759)
```

Tutorial: n-site states with MPS

[TODO: Add visualization of H]

```julia
ψ0 = MPS(i, "Z+")
nlayers = 6
function F(θ)
  ψθ = apply(U(θ, i; nlayers), ψ0)
  return -abs(inner(ψ', ψθ))^2
end

θ0 = zeros(nlayers * n)
θ = minimize(F, ∂F, θ0;
        nsteps=20, γ=0.1)
```

```julia
# |0⟩ = |Z+Z+...Z+⟩

# Minimize over θ:
# F(θ) = −|⟨ψ|U(θ)|0⟩|^2
#      = −|⟨ψ|θ⟩|2
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```

```
maxlinkdim(ψ0)
maxlinkdim(ψθ)
F(θ0), norm(∂F(θ0))
F(θ), norm(∂F(θ))
```

```
# 1 (product state)
# 2 (entangled state)
# (−0.556066, 0.895717)
# (−0.995230, 0.048939)
```

Future directions

- More AD, make ITensor fully differentiable (have some work to do, like tensor decompositions and general network contractions, more MPS/MPO functions. You will find bugs!).

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- Many ongoing projects and directions: quantum chemistry (for example UCC), real space parallel DMRG, TDVP, and TEBD, MPO compression tools, general approximate contraction techniques for unstructured networks, contracting and optimizing general tensor networks with AD, infinite MPS and tensor network tools like VUMPS and TDVP, trying out different network topologies for noisy circuit tomography, simulation and optimization.

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