Understanding quantum computation using pictures

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University of Amsterdam

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Quantum Computing 101

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- Spooky action at a distance, too strong nonlocal correlations, can't copy information, can't know the full state...
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- Then Feynmann said "not a bug, but a feature".
- And thus the field of quantum computing was born ($\approx$1980).

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Sequence of classical bits: $\vec{b} \in \{0, 1\}^n$. $\vec{b} = 00110101\ldots$
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But it is harder than you might think.

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Amazing! But then why haven't we solved world hunger yet?

The big problem of quantum computing

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we need to *measure* it.

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Our amazing trick fails :'(

(unless we use other really smart tricks)

Quantum gates as rotations

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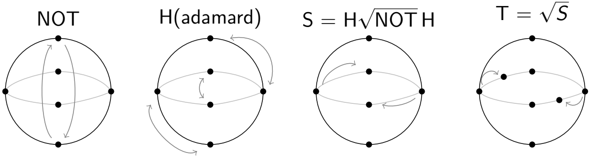

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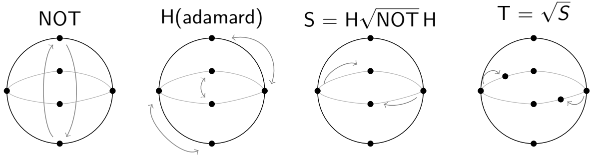

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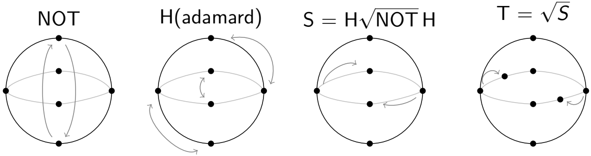

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- This is an *approximately universal* gate set.

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$$\mathsf{S} \;=\; \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \qquad \mathsf{H} \;=\; \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

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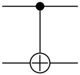
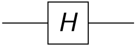
... but nobody wants to deal with these things directly.

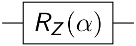
Quantum gates as gates

$$X \;=\; \text{NOT} \;=\;$$  $$=\; \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\text{CNOT} \;=\;$$  $$=\; \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$\text{Hadamard} \;=\;$$ 

$$=\; \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

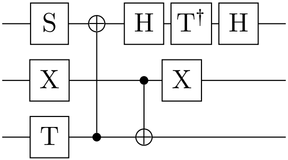
$$R_Z(\alpha) \;=\;$$ 

$$=\; \begin{pmatrix} 1 & 0 \\ 0 & e^{i\alpha} \end{pmatrix}$$

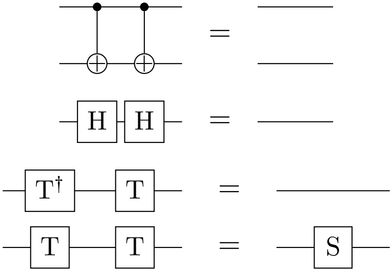
$$Z := R_Z(\pi) \qquad S := R_Z(\tfrac{\pi}{2}) \qquad T := R_Z(\tfrac{\pi}{4})$$

Quantum circuits

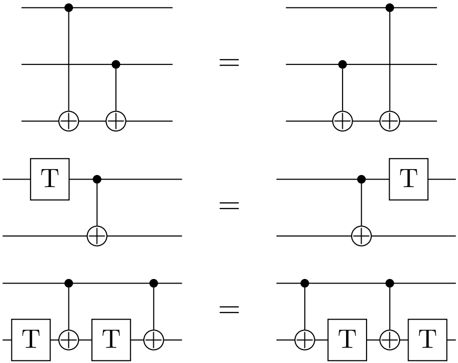
An example quantum circuit:



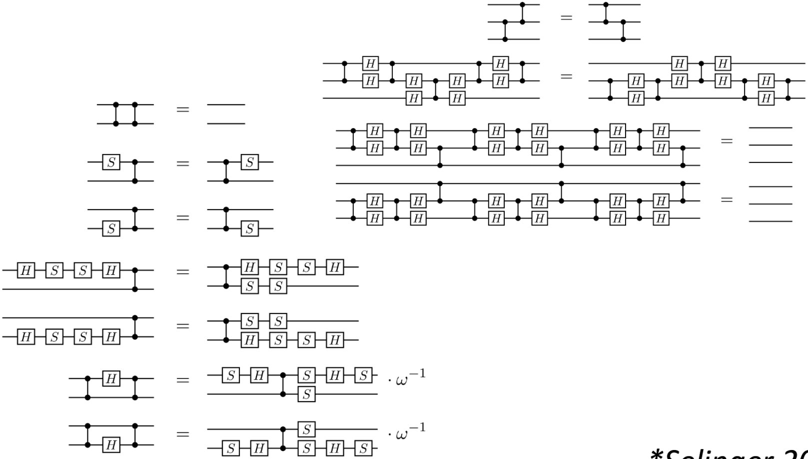
Circuit identities



Gate commutation

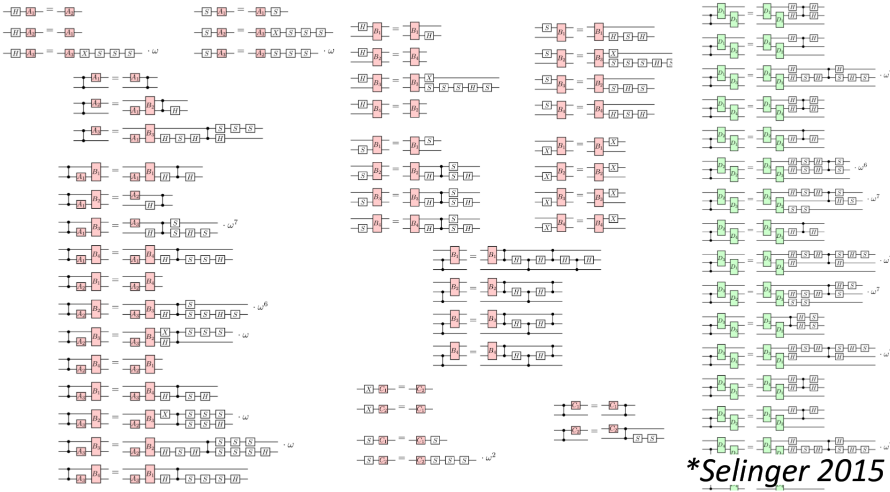


More circuit equalities



**Selinger 2015*

And more circuit equalities



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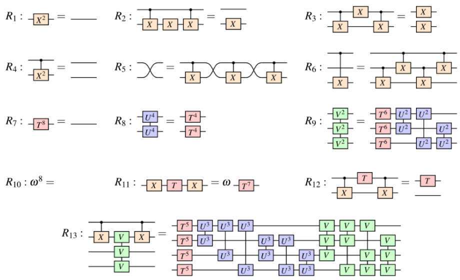
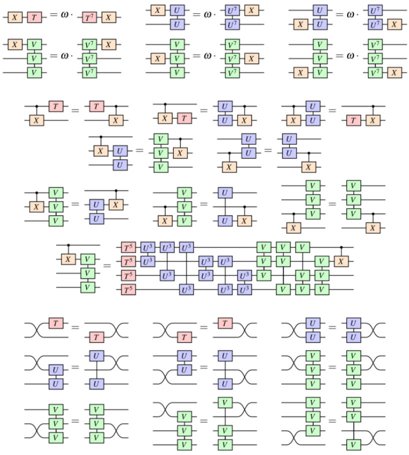
And even more circuit equalities





*Amy, Chen, & Ross 2018

Quantum circuits bad!

Why is this so terrible?

- Choice of gates is a bit arbitrary
- The notation is not “quantum native”
- Wires are rigid going from left-to-right

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The *ZX-calculus* essentially gets rid of these problems

The ZX-calculus

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Used in:

- Quantum circuit compilation and simulation
- Measurement-based quantum computation
- Surface codes and lattice surgery
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It is also a convenient tool for day-to-day quantum reasoning

Spiders

What gates are to circuits, *spiders* are to ZX-diagrams.

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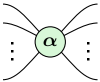
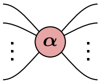
Z-spider

$$|0\cdots0\rangle\langle0\cdots0| + e^{i\alpha}\,|1\cdots1\rangle\langle1\cdots1|$$



X-spider

$$|+\cdots+\rangle\langle+\cdots+| + e^{i\alpha}\,|-\cdots-\rangle\langle-\cdots-|$$



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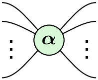

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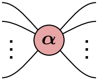

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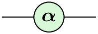
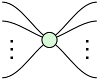
For example:



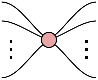
$$= |0\rangle\langle0| + e^{i\alpha}\,|1\rangle\langle1| = \begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} + \begin{pmatrix}0 & 0\\ 0 & e^{i\alpha}\end{pmatrix} = \begin{pmatrix}1 & 0\\ 0 & e^{i\alpha}\end{pmatrix}$$

Spiders cont.

If $\alpha = 0$ we drop the label:



$$= \quad |0 \cdots 0\rangle\langle 0 \cdots 0| + |1 \cdots 1\rangle\langle 1 \cdots 1|$$



$$= \quad |+ \cdots +\rangle\langle + \cdots +| + |- \cdots -\rangle\langle - \cdots -|$$

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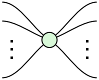

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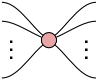
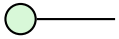
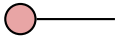
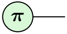


$$= \quad |+\cdots +\rangle\langle +\cdots +| + |-\cdots -\rangle\langle -\cdots -|$$

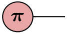
Example:

 $= \quad |0\rangle + |1\rangle \; = \sqrt{2}\,|+\rangle$

 $= \quad |+\rangle + |-\rangle \; = \sqrt{2}\,|0\rangle$



$= \quad |0\rangle - |1\rangle \; = \sqrt{2}\,|-\rangle$



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We will ignore these $\sqrt{2}$ scalar factors

Formal composition

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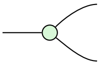
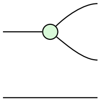
Vertical composition gives tensor product:



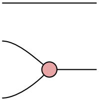
$$= \begin{pmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix}$$



$$= \begin{pmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Formal composition

Other tensor product:

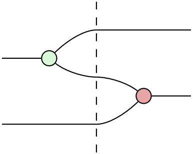


$$= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{pmatrix}$$

Formal composition

Horizontal composition is regular composition of linear maps:

 $=$

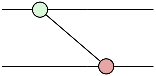
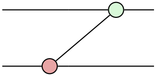
$$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0&1&0&0&0&0\\0&1&1&0&0&0&0&0\\0&0&0&0&1&0&0&1\\0&0&0&0&0&1&1&0\end{pmatrix}\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{pmatrix}$$

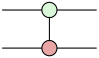
Building ZX-diagrams

Any ZX-diagram is built by simply iterating
these vertical and horizontal compositions

Symmetries

Note:

 $=$ 

Hence, we may write 

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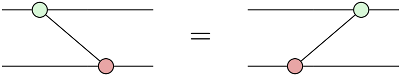
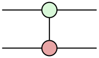
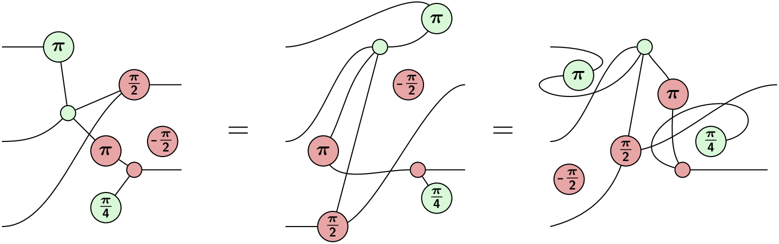


Hence, we may write 

In general: *only connectivity matters*



ZX-diagrams summary

- Two types of generators: Z-spiders and X-spiders
- Can compose both horizontally and vertically
- Wires can connect every which way

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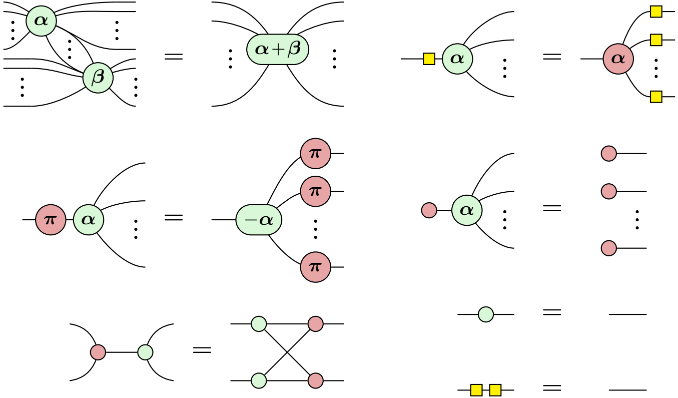
How powerful are ZX-diagrams as a representation?

Theorem

ZX-diagrams are *universal*: any linear map between qubits can be represented as a ZX-diagram.

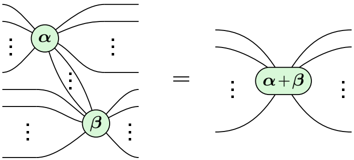
So far it's just notation. What can we do with it?

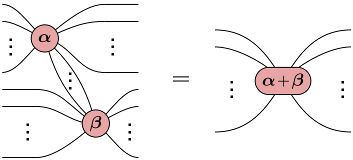
Rules for ZX-diagrams: The ZX-calculus



$\forall \alpha, \beta \in [0, 2\pi]$

Spider fusion





Connected spiders of same colour fuse

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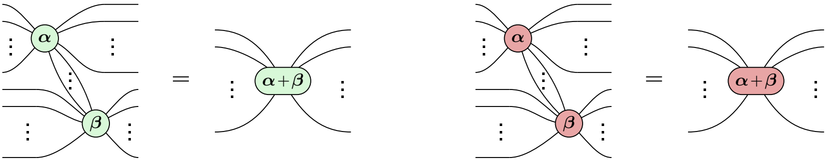

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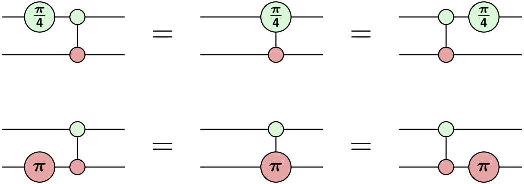
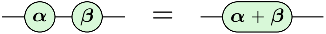
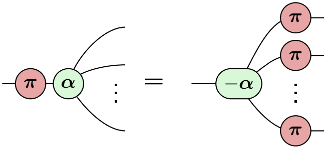
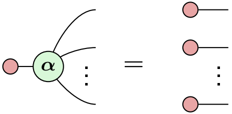




State and pi-copy





π's and phase-free states copy through the other colour

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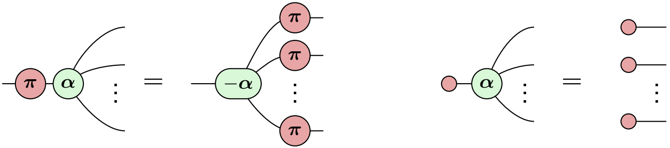

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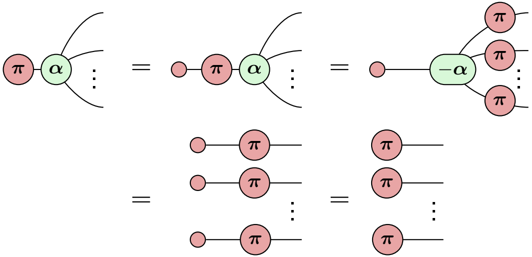
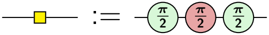
Combining rules:



Hadamards and colour-changing

Definition of Hadamard in ZX:



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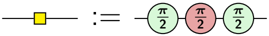
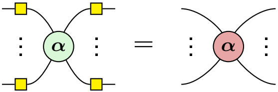


Rules:



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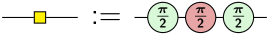

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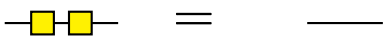
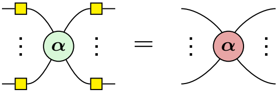
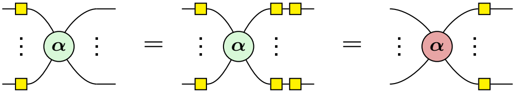




Derived rule: *commuting Hadamards changes colour*



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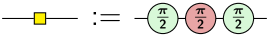

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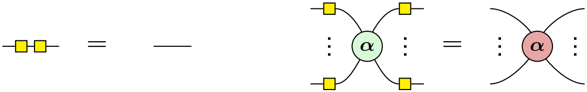

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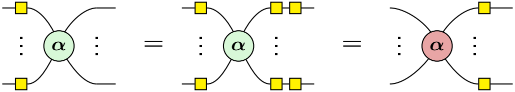
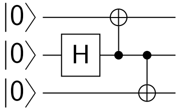


Consequence: *Everything in ZX holds with colours reversed*

Example 1: GHZ-preparation circuit

GHZ-state is $|000\rangle + |111\rangle$.
The following circuit creates a GHZ-state:



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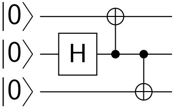
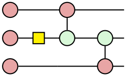


Proof:



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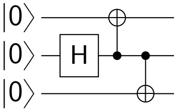

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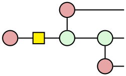

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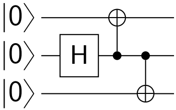

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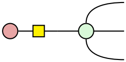

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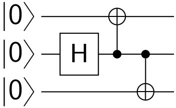

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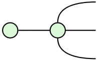

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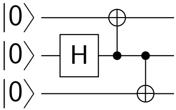

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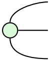
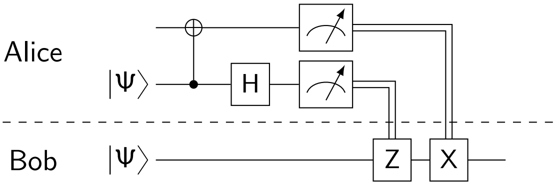


Example 2: Teleportation

Let $|\Psi\rangle$ represent a side of a Bell state.
Then this is the standard quantum teleportation protocol:



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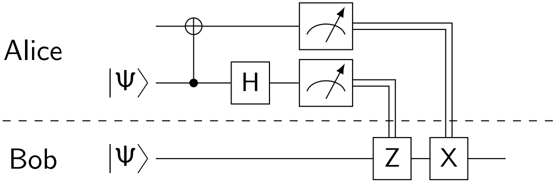

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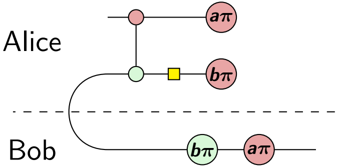

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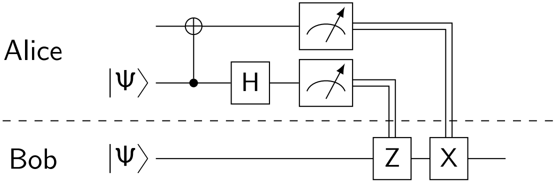

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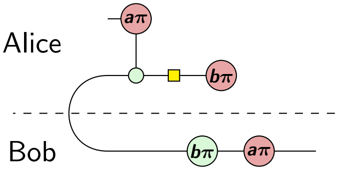

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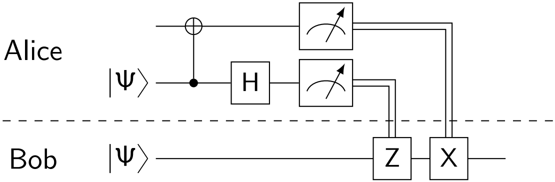

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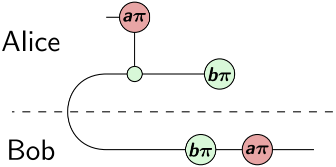

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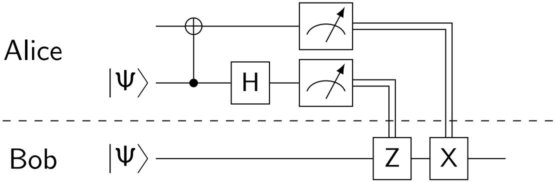

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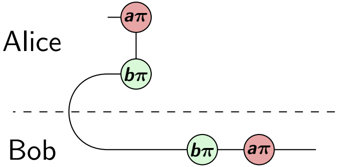

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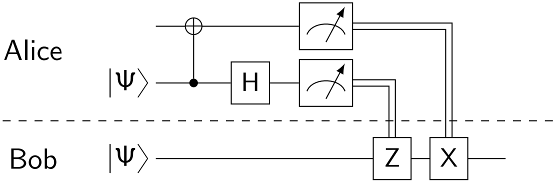

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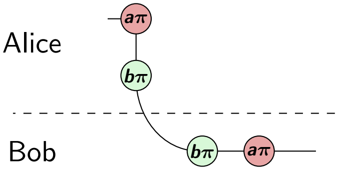

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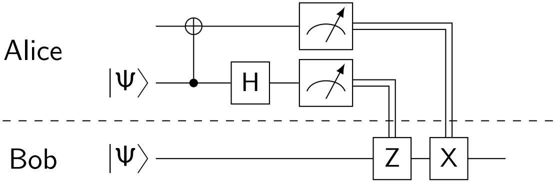

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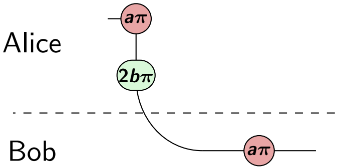

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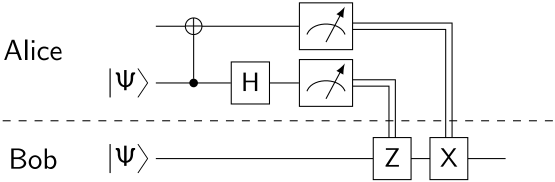

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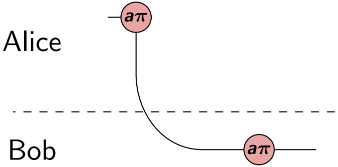

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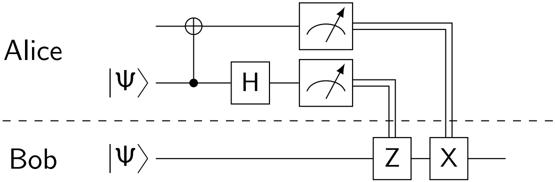

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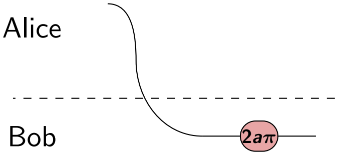

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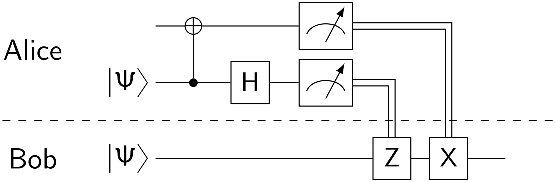

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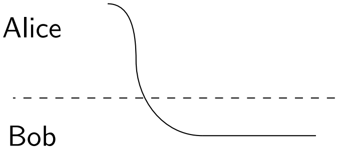
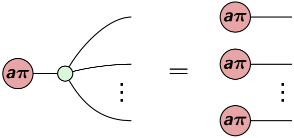
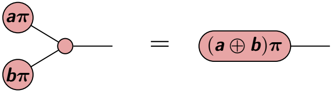


Bialgebra

Z-spiders act like COPY; X-spiders act like XOR:





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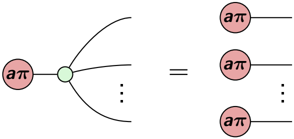
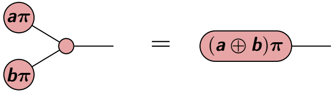
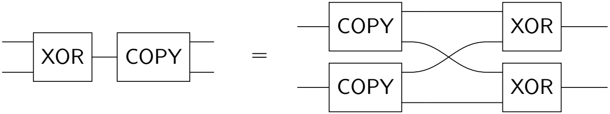




Classically we have:



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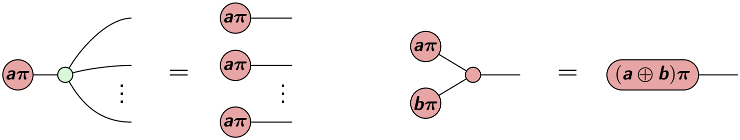

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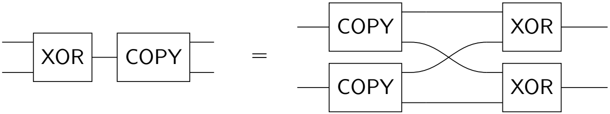
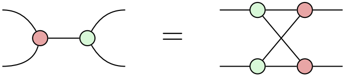
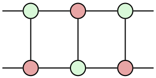


Hence:



Example 3: Three CNOTs make SWAP



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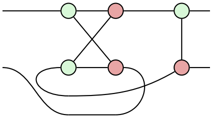

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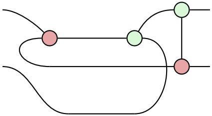

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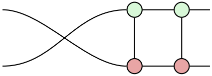

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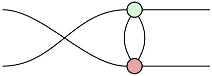

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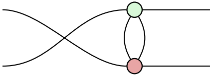

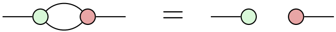

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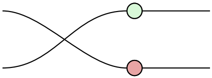

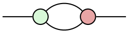

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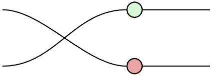

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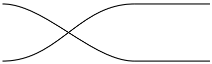
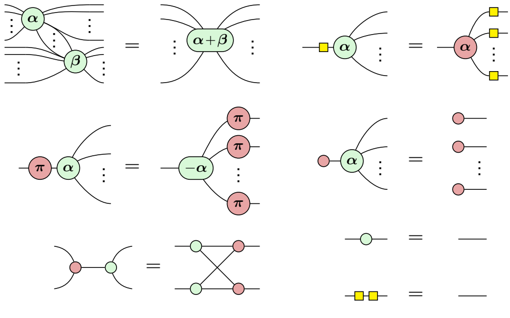


Rules for ZX-diagrams: The ZX-calculus

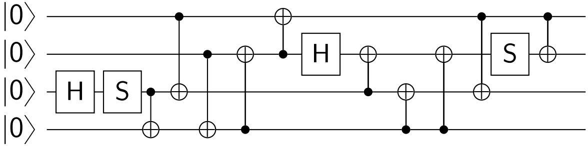


$$\alpha, \beta \in [0, 2\pi]$$

- All derivations hold in any orientation
- All derivations hold with colours interchanged
- All derivations hold with phases negated

Example 4: Detecting entanglement

Consider the following circuit:



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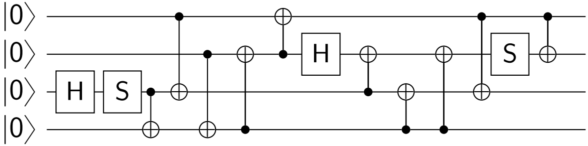

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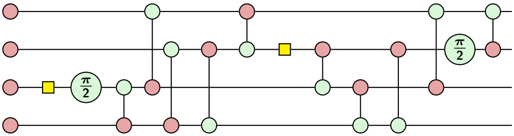
Step 1: Write it as a ZX-diagram



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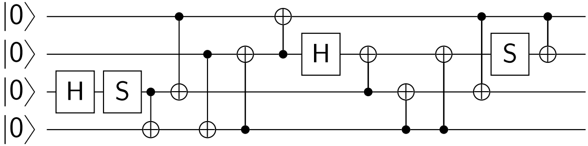

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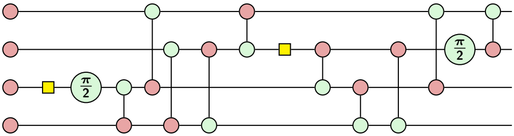

Step 2: Open up PyZX

Completeness

How much can we prove using the rules?

Theorem

The rules shown so far suffice to show any true equality between *Clifford* diagrams (where phases are $\frac{\pi}{2}$).

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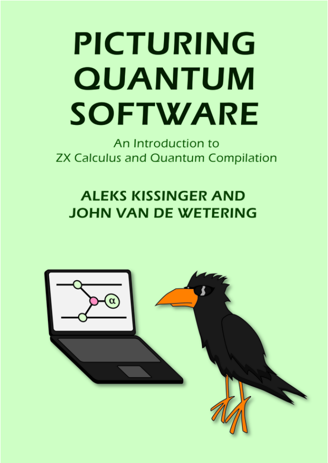
Theorem

These rules + one more suffice to show *any* true equality.

New book on quantum compilation



- Over 500 pages and 100 exercises
- Synthesis of quantum circuits
- Optimisation, verification, simulation
- A new approach to understanding quantum error correction
- And all this using ZX-diagrams!
- And available for free for everyone!

https://github.com/zxcalc/book

Classical simulation using ZX

Veni proposal: Combine tensor network techniques with *stabiliser decomposition* approach.

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- Replace ‘expensive’ resource states by sum of ‘cheap’ states.
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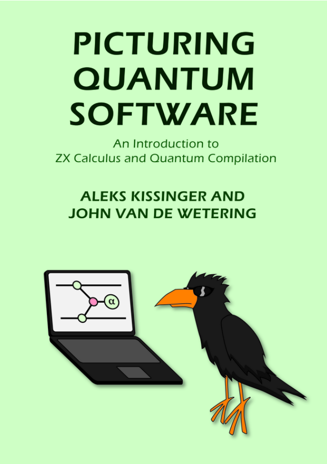
Apply this to:

- Simulate quantum computations
- Calculate properties of condensed matter systems
- SAT/model counting problems

Thank you for your attention!

Kissinger & vdW 2021, arXiv:2109.01076
Simulating quantum circuits with ZX-calculus reduced stabiliser decompositions



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