

An introduction to the ZX-calculus

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UCL, PPLV group

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QInfo seminar

Outline

Process theories

The calculus

From quantum circuits to ZX

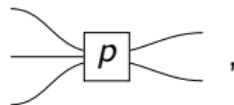
From MBQC to ZX

A logician's view

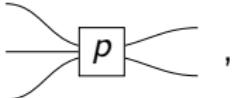
Applications

Process theories

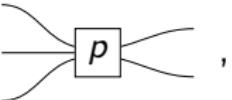
- ▶ A *process* is drawn as a box:



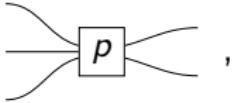
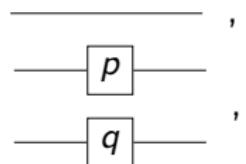
Process theories

- ▶ A *process* is drawn as a box:  ,
- ▶ There is a special process that “does nothing”: _____ ,

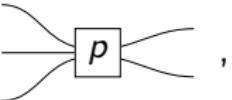
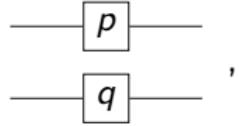
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- ▶ Two processes can be *composed*

Process theories

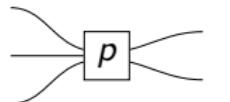
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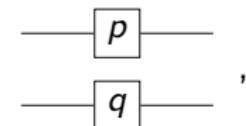
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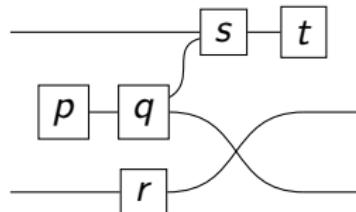
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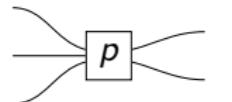


Example of a composite process:



Process theories

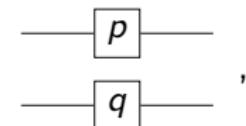
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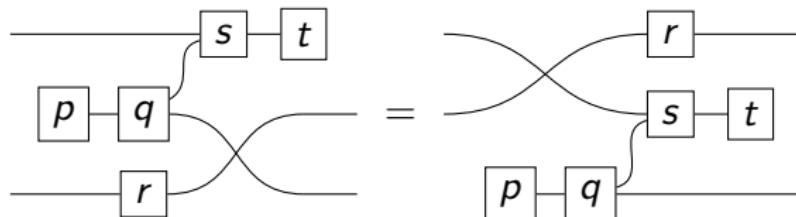
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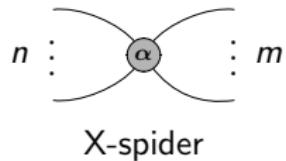
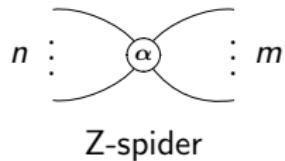
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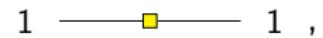
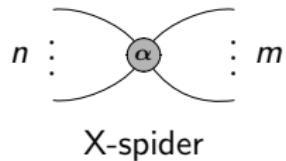
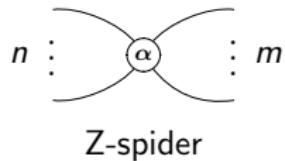
Generators



1 ————— ————— 1 ,

Hadamard gate

Generators



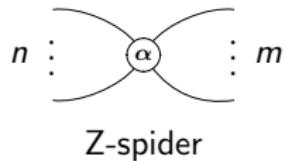
Z-spider

X-spider

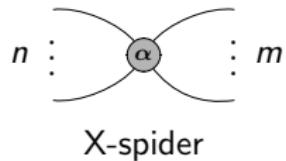
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where $\alpha \in [0, 2\pi)$ is called a *phase*. Example:

Generators



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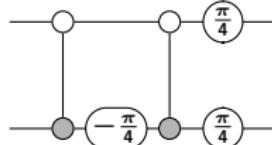
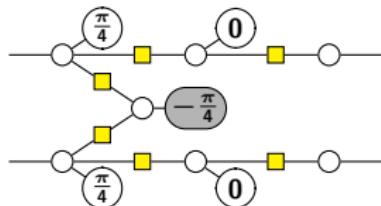


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Translation to linear maps

A diagram with n inputs and m outputs is translated to a linear map $\mathbb{C}^{2^n} \rightarrow \mathbb{C}^{2^m}$,

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$$\begin{array}{c} \vdots \quad \alpha \quad \vdots \\ \text{Diagram: two lines entering a circle labeled } \alpha, \text{ which is shaded gray, then splits into two lines.} \\ \vdots \quad \alpha \quad \vdots \end{array} \mapsto |+ \cdots +\rangle\langle + \cdots +| + e^{i\alpha} |- \cdots -\rangle\langle - \cdots -|$$

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Sequential composition is interpreted as matrix multiplication, and parallel composition as the Kronecker product

Examples



Examples

$$\bullet \longrightarrow \mapsto |0\rangle$$

Examples

$$\begin{array}{l} \text{---} \mapsto |0\rangle \\ \text{---} \mapsto \end{array}$$

○

π

Examples

$$\begin{aligned} \bullet &\longrightarrow |0\rangle \\ \textcircled{\pi} &\longrightarrow |1\rangle \end{aligned}$$

Examples

 $\mapsto |0\rangle$
 $\mapsto |1\rangle$
 \mapsto

Examples

$$\begin{aligned} \bullet &\longrightarrow |0\rangle \\ \textcircled{\pi} &\longrightarrow |1\rangle \\ \circ &\longrightarrow |+\rangle \end{aligned}$$

Examples

\bullet $\mapsto |0\rangle$
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Examples

$$\bullet \longrightarrow \mapsto |0\rangle$$

$$\circlearrowleft \pi \longrightarrow \mapsto |1\rangle$$

$$\circlearrowleft \longrightarrow \mapsto |+\rangle$$

$$\circlearrowleft \pi \longrightarrow \mapsto |-\rangle$$

Examples

$$\begin{array}{l} \text{---} \rightarrow |0\rangle \\ \text{---} \rightarrow |1\rangle \\ \text{---} \rightarrow |+\rangle \\ \text{---} \rightarrow |-\rangle \\ \text{---} \text{---} \rightarrow \end{array}$$

Examples

$$\begin{aligned} \bullet \text{---} &\mapsto |0\rangle \\ \text{---} \bullet &\mapsto |1\rangle \\ \circ \text{---} &\mapsto |+\rangle \\ \text{---} \circ &\mapsto |-\rangle \\ \text{---} \bullet &\quad \bullet \text{---} \mapsto |0\rangle\langle 0| \end{aligned}$$

Examples

$$\begin{array}{ll} \text{---} \bullet \longrightarrow & |0\rangle \\ \text{---} \circlearrowleft \pi \longrightarrow & |1\rangle \\ \text{---} \circlearrowleft \bullet \longrightarrow & |+\rangle \\ \text{---} \circlearrowleft \circlearrowleft \pi \longrightarrow & |-\rangle \\ \text{---} \bullet \quad \text{---} \bullet \longrightarrow & |0\rangle\langle 0| \\ \text{---} \circlearrowleft \pi \quad \text{---} \bullet \longrightarrow & \end{array}$$

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Examples

- $\mapsto |0\rangle$
- $\mapsto |1\rangle$
- $\mapsto |+\rangle$
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- ●— $\mapsto |0\rangle\langle 0|$
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Examples

- → $|0\rangle$
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Equations

$$\begin{array}{c} \text{Diagram showing two nodes } \alpha \text{ and } \beta \text{ with multiple outgoing edges.} \\ \vdots \\ \alpha \\ \vdots \\ \beta \end{array} \stackrel{(\mathbf{f})}{=} \begin{array}{c} \text{Diagram showing a single node } \alpha + \beta \text{ with multiple outgoing edges.} \\ \vdots \end{array}$$

$$\begin{array}{c} \text{Diagram showing a central node } \alpha \text{ connected to four yellow squares.} \\ \vdots \\ \text{Yellow square} \\ \vdots \\ \text{Yellow square} \end{array} \stackrel{(\mathbf{h})}{=} \begin{array}{c} \text{Diagram showing a single node } \alpha \text{ with multiple outgoing edges.} \\ \vdots \end{array}$$

$$\begin{array}{c} \text{Diagram showing a single node with a single outgoing edge.} \\ \text{---} \end{array} \stackrel{(\mathbf{i1})}{=} \begin{array}{c} \text{Diagram showing a single node with a single outgoing edge.} \\ \text{---} \end{array}$$

$$\begin{array}{c} \text{Diagram showing a central node } \alpha \text{ with two nodes } \pi \text{ on its left.} \\ \vdots \\ \pi \\ \text{---} \end{array} \stackrel{(\pi)}{=} \begin{array}{c} \text{Diagram showing a central node } -\alpha \text{ with three nodes } \pi \text{ on its right.} \\ \vdots \\ \pi \\ \text{---} \end{array}$$

$$\begin{array}{c} \text{Diagram showing a central node } \alpha \text{ with three nodes on its left.} \\ \vdots \\ \text{---} \end{array} \stackrel{(\mathbf{c})}{=} \begin{array}{c} \text{Diagram showing three nodes on the left.} \\ \vdots \\ \text{---} \end{array}$$

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$$\begin{array}{c} \text{Diagram showing a central node with two nodes on its left and two nodes on its right.} \\ \text{---} \end{array} \stackrel{(\mathbf{b})}{=} \begin{array}{c} \text{Diagram showing a central node with two nodes on its left and two nodes on its right.} \\ \text{---} \end{array}$$

where addition is modulo 2π .

Equations

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$$\begin{array}{c} \text{Diagram showing a central node } \alpha \text{ with two nodes } \pi \text{ attached.} \\ \vdots \\ \pi \\ \alpha \\ \vdots \\ \pi \end{array} \stackrel{(\pi)}{=} \begin{array}{c} \text{Diagram showing a central node } -\alpha \text{ with three nodes } \pi \text{ attached.} \\ \vdots \\ \pi \\ \pi \\ \pi \end{array}$$

$$\begin{array}{c} \text{Diagram showing a central node } \alpha \text{ with three outgoing edges.} \\ \vdots \end{array} \stackrel{(c)}{=} \begin{array}{c} \text{Diagram showing three separate nodes.} \\ \text{---} \\ \text{---} \\ \vdots \\ \text{---} \end{array}$$

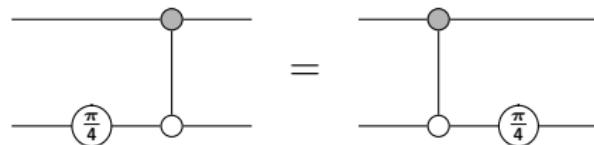
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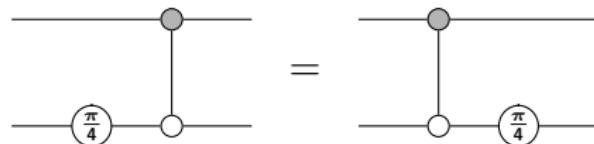
where addition is modulo 2π .

The equations identify linear maps *up to a global non-zero scalar!!!*

Example

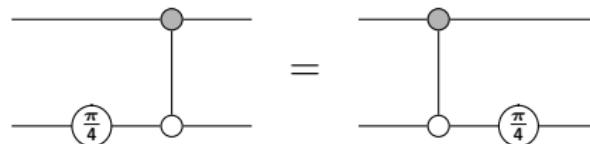


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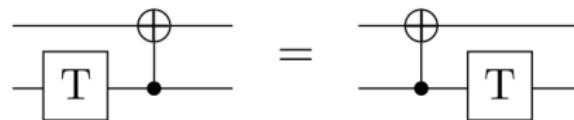


Which we recognise as

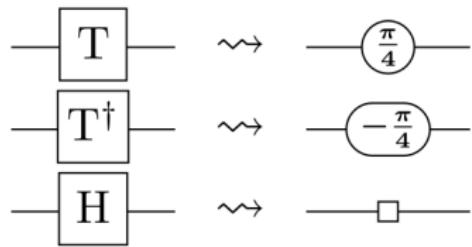
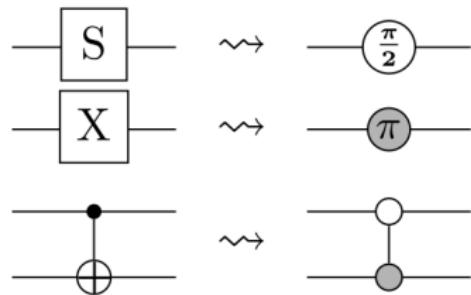
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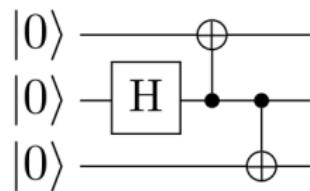
From quantum circuits to ZX



1

¹Image credit: John van de Wetering

Example: GHZ state



From measurement patterns to ZX

A *measurement pattern*² is a sequence of commands acting on qubits:

²Danos, Kashefi and Panangaden: *The Measurement Calculus*, 2007.

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- ▶ $M_k^{\lambda, \alpha}$ – apply a projective measurement,
- ▶ X_n^s or Z_n^s – apply Pauli-X or Pauli-Z operator if $s = 1$ (do nothing if $s = 0$)

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Example

Consider the following pattern:

$$N_2 E_{12} M_1^{XY,0} X_2^{s_1}$$

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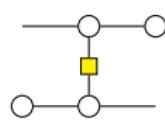
It has two branches (=possible computations), depicted as following ZX-diagrams:

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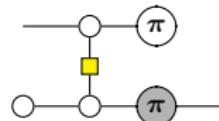
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$$s_1 = 0$$



$$s_1 = 1$$

A logician's view

The ZX-calculus is:

³This requires adding some rules to the ones we've seen.

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- ▶ *Sound*: If two diagrams are equal, then the corresponding linear maps are equal,

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The ZX-calculus is:

- ▶ *Sound*: If two diagrams are equal, then the corresponding linear maps are equal,
- ▶ *Universal*: Every linear map $\mathbb{C}^{2^n} \rightarrow \mathbb{C}^{2^m}$ can be represented as a diagram,

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A logician's view

The ZX-calculus is:

- ▶ *Sound*: If two diagrams are equal, then the corresponding linear maps are equal,
- ▶ *Universal*: Every linear map $\mathbb{C}^{2^n} \rightarrow \mathbb{C}^{2^m}$ can be represented as a diagram,
- ▶ *Complete*: If two linear maps are equal, then the corresponding diagrams are equal³.

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Applications

- ▶ Classical simulation of quantum circuits
- ▶ Circuit optimisation

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 - ▶ Kissinger and van de Wetering: *Simulating quantum circuits with ZX-calculus reduced stabiliser decompositions*, Quantum Sci. Technol, 2022
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 - ▶ Kissinger and van de Wetering: *Simulating quantum circuits with ZX-calculus reduced stabiliser decompositions*, Quantum Sci. Technol, 2022
 - ▶ Cam, Martiel: *Speeding up quantum circuits simulation using ZX-Calculus*, arXiv:2305.02669, 2023
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Applications

- ▶ Classical simulation of quantum circuits
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- ▶ Error correction
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Further reading

- ▶ ZX-website: zxcalculus.com
- ▶ John van de Wetering: *ZX-calculus for the working quantum computer scientist*, arXiv:2012.13966
- ▶ Bob Coecke and Aleks Kissinger: *Picturing Quantum Processes*, CUP 2017

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Thank you for your attention!