An Overview of Circuit Optimisation with the ZX Calculus

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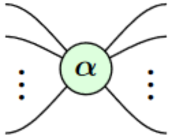
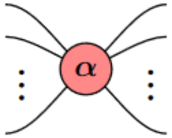
UNIVERSITY OF OXFORD

HASHBERG

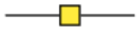
ZX Calculus Tensors



$= |0...0\rangle\langle 0...0| + e^{i\alpha}|1...1\rangle\langle 1...1|$



$= |+...+\rangle\langle +...+| + e^{i\alpha}|-...-\rangle\langle -...-|$


$= |+\rangle\langle 0| + |-\rangle\langle 1|$

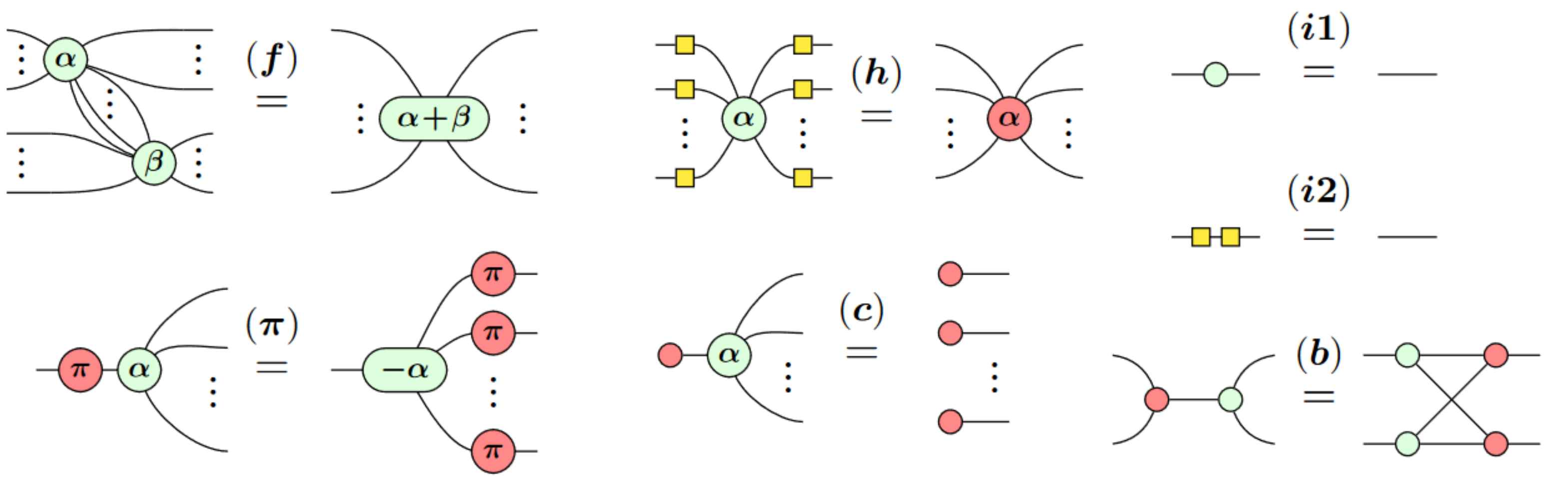
$= |0\rangle\langle 0| + |1\rangle\langle 1|$


$= \sum_{i,j\in\{0,1\}} |ij\rangle\langle ji|$

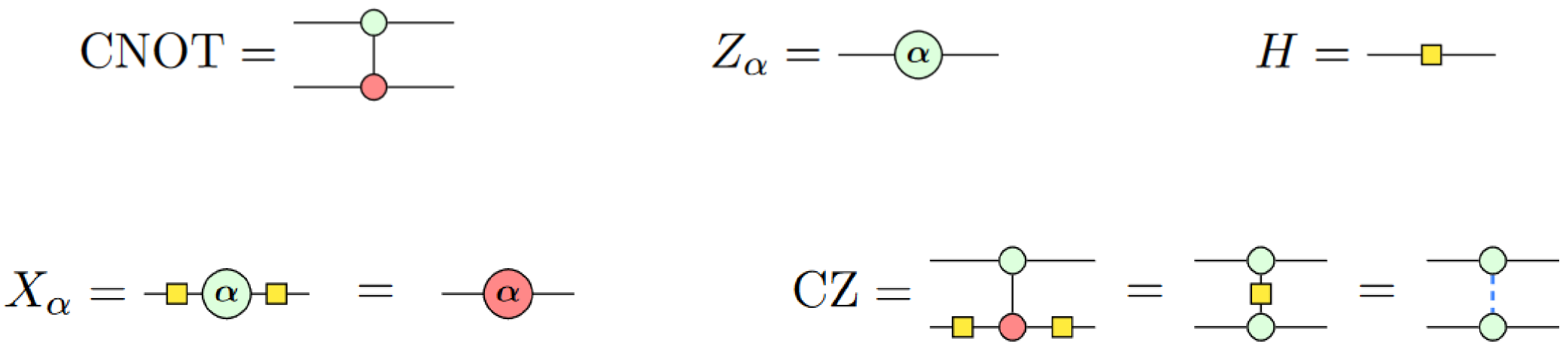

$= |00\rangle + |11\rangle$


$= \langle 00| + \langle 11|$

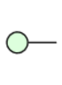
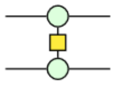
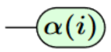
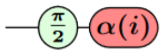
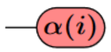
ZX Calculus Rules



Quantum Circuits



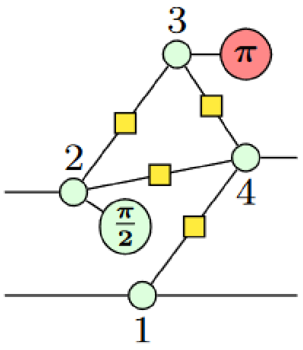
MBQC

operator	N_i	E_{ij}	$\langle +_{\mathrm{XY},\alpha(i)} \vert_i$	$\langle +_{\mathrm{XZ},\alpha(i)} \vert_i$	$\langle +_{\mathrm{YZ},\alpha(i)} \vert_i$
diagram					

Example 2.15. The measurement pattern with the qubit register $V = \{1, 2, 3, 4\}$, input and output sets $I = \{1, 2\}$ and $O = \{1, 4\}$ and the sequence of commands

$$M_2^{\mathrm{XY},\frac{\pi}{2}} M_3^{\mathrm{YZ},\pi} E_{14} E_{23} E_{24} E_{34} N_3 N_4$$

is represented by the following ZX-diagram:



arXiv > quant-ph > arXiv:2003.01664

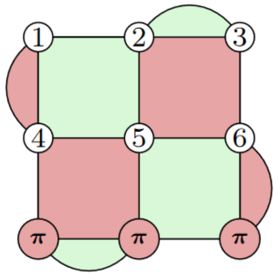
Quantum Physics

[Submitted on 3 Mar 2020 (v1), last revised 23 Mar 2021 (this version, v3)]

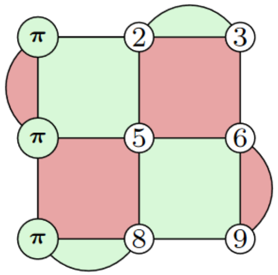
There and back again: A circuit extraction tale

Miriam Backens, Hector Miller-Bakewell, Giovanni de Felice, Leo Lobski, John van de Wetering

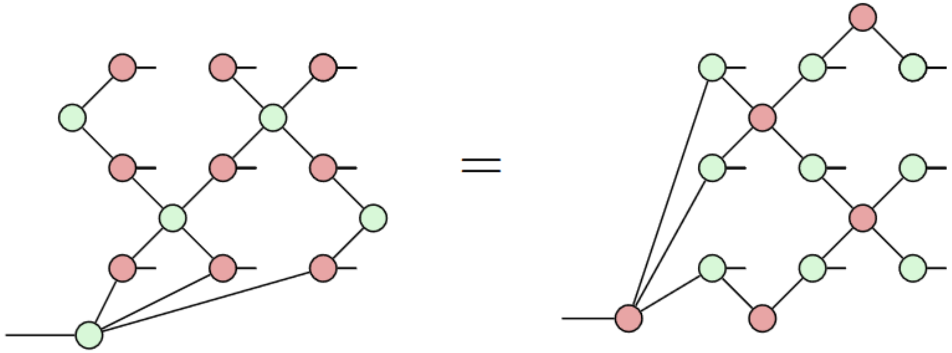
CSS Codes



$\rightsquigarrow \quad \overline{\mathcal{X}} := X_7 X_8 X_9$



$\rightsquigarrow \quad \overline{\mathcal{Z}} := Z_1 Z_4 Z_7$



arXiv > quant-ph > arXiv:2204.14038

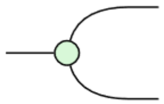
Quantum Physics

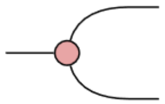
[Submitted on 29 Apr 2022]

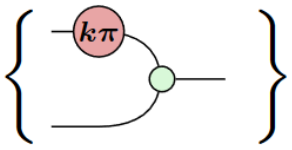
Phase-free ZX diagrams are CSS codes

Aleks Kissinger

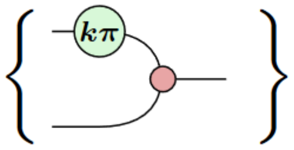
Surface Code Lattice Surgery

$Z\text{-}split$:= 

$X\text{-}split$:= 

$Z\text{-}merge$:= 

$_{k=0,1}$

$X\text{-}merge$:= 

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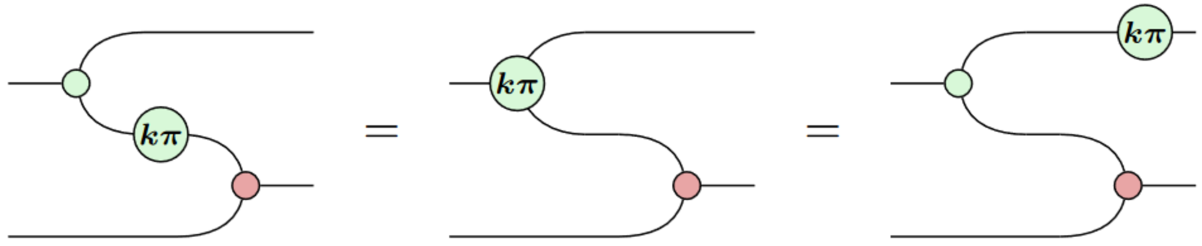


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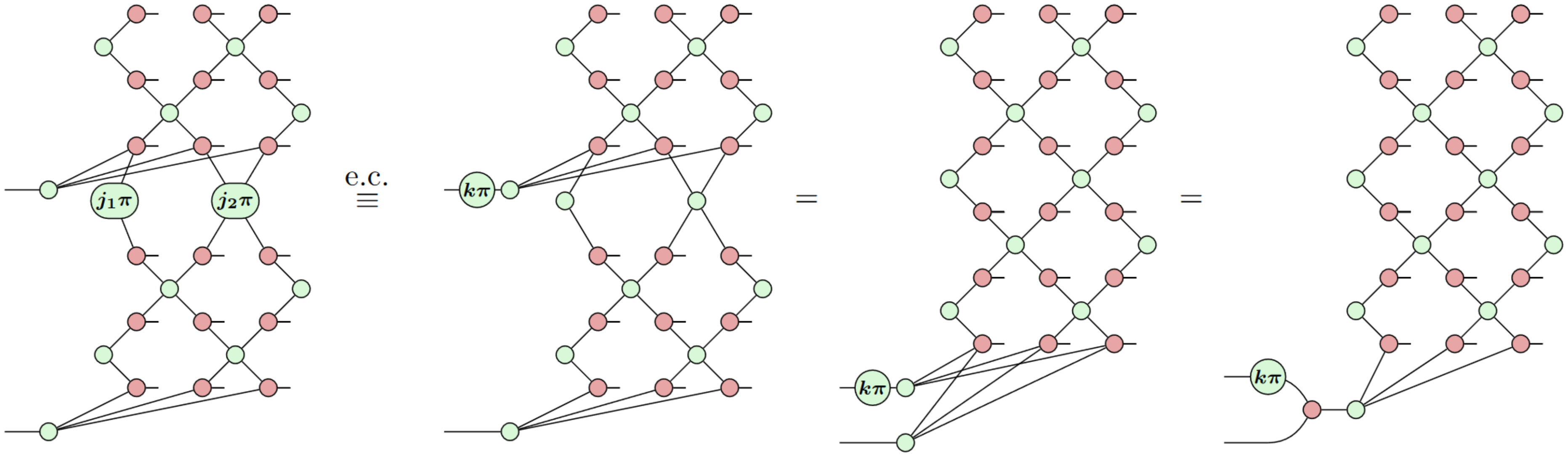

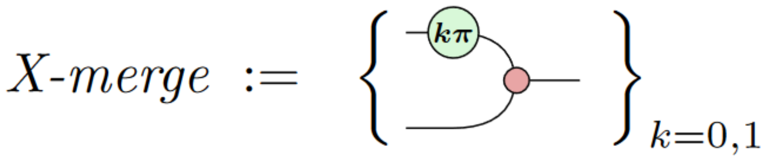

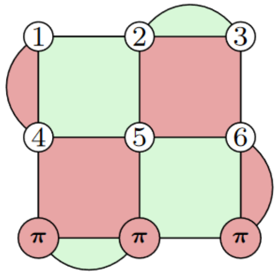

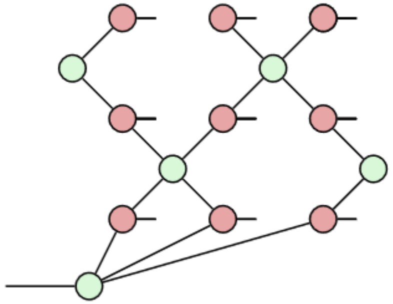

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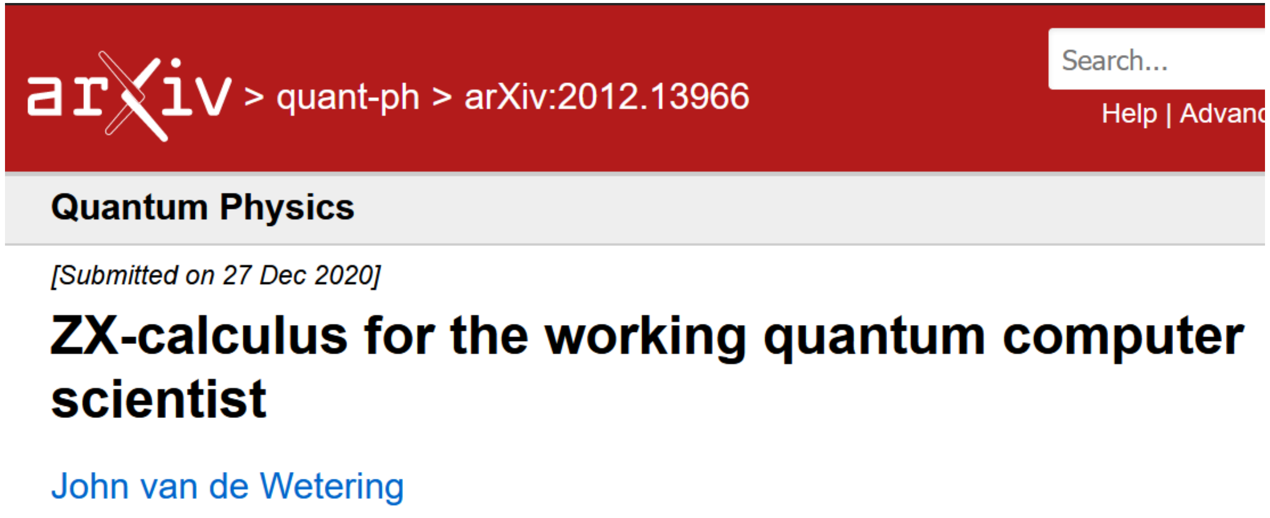
References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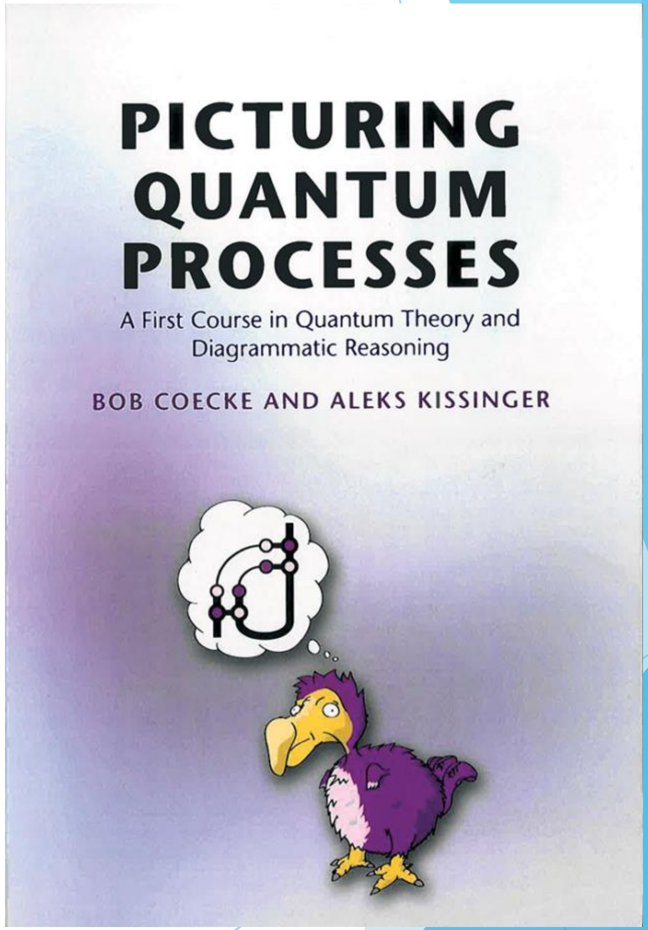
[Submitted on 27 Dec 2020]
ZX-calculus for the working quantum computer scientist
John van de Wetering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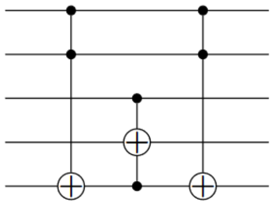
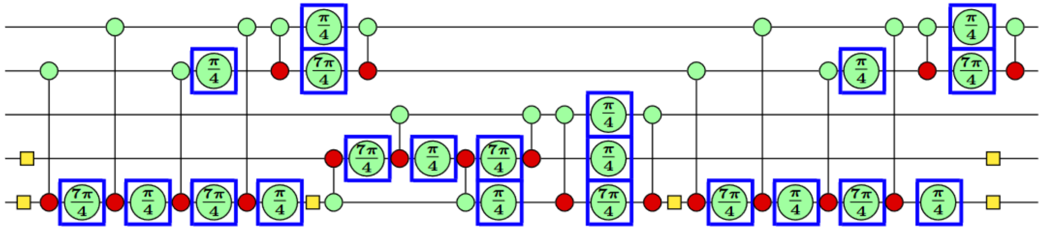
A First Course in Quantum Theory and Diagrammatic Reasoning
BOB COECKE AND ALEKS KISSINGER

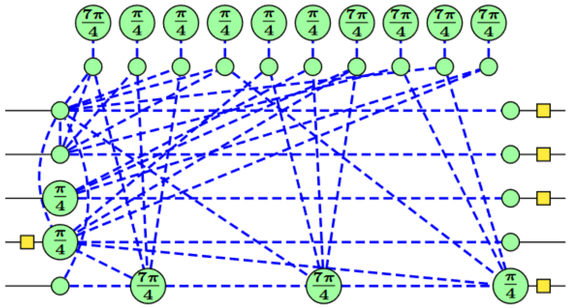
T-Count Reduction



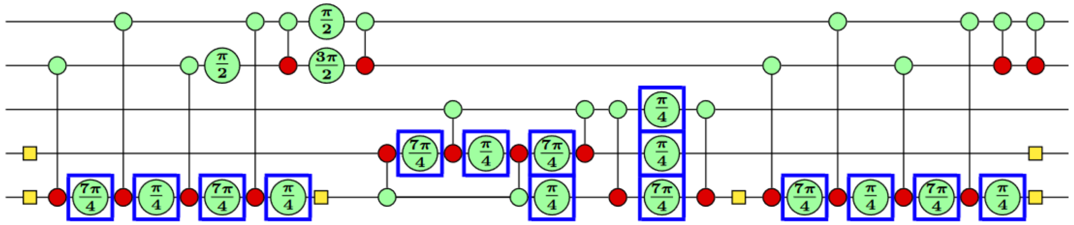
(a) Original circuit



(b) The circuit expanded as a ZX-diagram, with 21 T gates.



(c) Simplified ZX-diagram.



(d) 15 T gates remain after phase-teleportation.

arXiv > quant-ph > arXiv:1904.04735

Quantum Physics

[Submitted on 9 Apr 2019 (v1), last revised 1 May 2020 (this version, v2)]

PyZX: Large Scale Automated Diagrammatic Reasoning

Aleks Kissinger, John van de Wetering

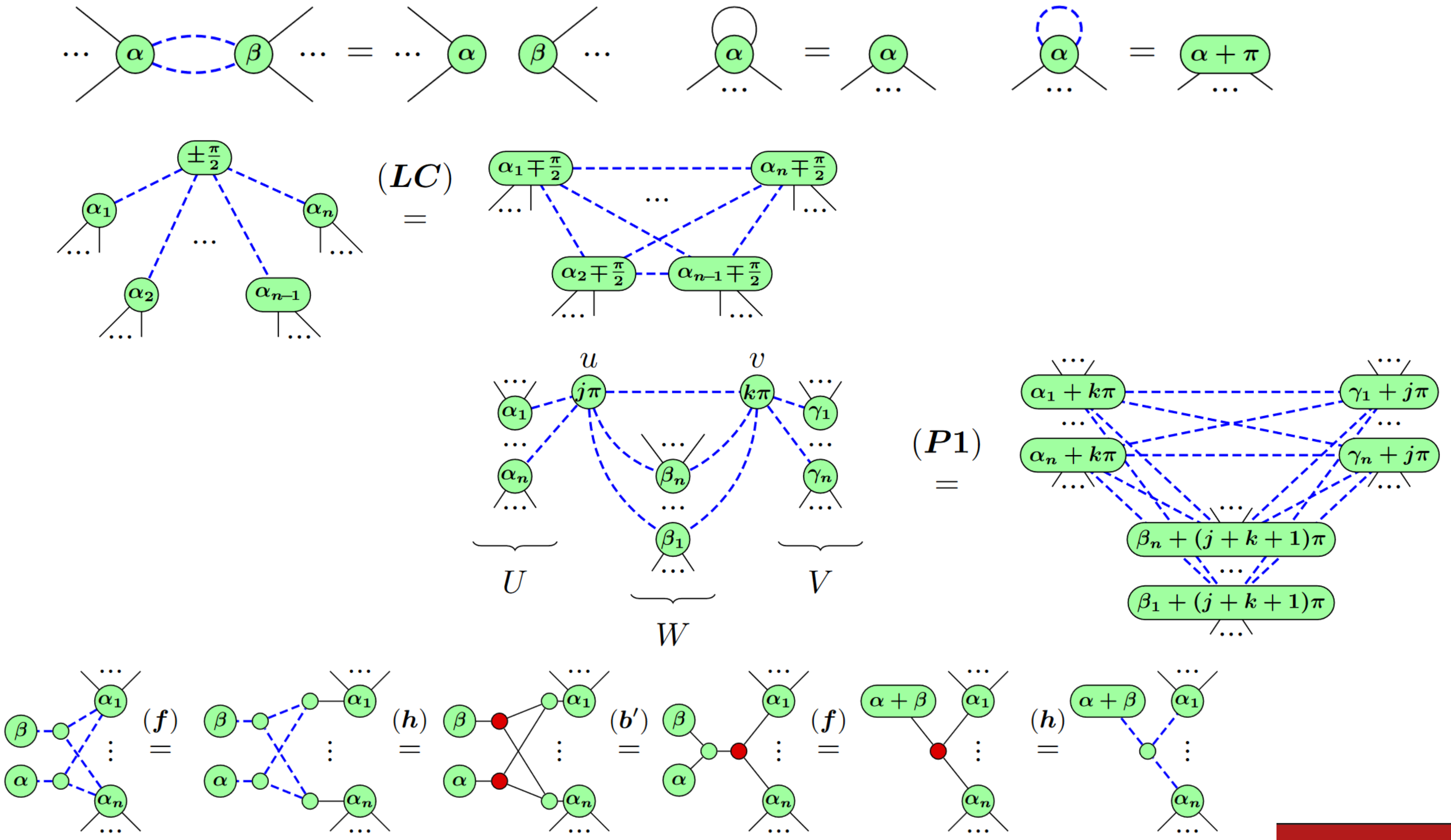
arXiv > quant-ph > arXiv:1903.10477

Quantum Physics

[Submitted on 25 Mar 2019 (v1), last revised 17 Jan 2020 (this version, v3)]

Reducing T-count with the ZX-calculus

Aleks Kissinger, John van de Wetering



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Circuit	n	T	Best prev.	Method	PyZX	PyZX+TODD
adder$_8$ [3]	**24**	**399**	**213**	**RM$_m$**	**173**	**167**
Adder8 [27]	23	266	56	NRSCM	56	56
Adder16 [27]	47	602	120	NRSCM	120	120
Adder32 [27]	95	1274	248	NRSCM	248	248
Adder64 [27]	191	2618	504	NRSCM	504	504
barenco-tof3 [27]	5	28	16	Tpar	16	16
barenco-tof4 [27]	7	56	28	Tpar	28	28
barenco-tof5 [27]	9	84	40	Tpar	40	40
barenco-tof10 [27]	19	224	100	Tpar	100	100
tof$_3$ [27]	5	21	15	Tpar	15	15
tof$_4$ [27]	7	35	23	Tpar	23	23
tof$_5$ [27]	9	49	31	Tpar	31	31
tof$_{10}$ [27]	19	119	71	Tpar	71	71
csla-mux$_3$ [27]	*15*	*70*	*58*	*RM$_r$*	*62*	**45**
csum-mux$_9$ [27]	*30*	*196*	*76*	*RM$_r$*	*84*	**72**
cycle17$_3$ [3]	**35**	**4739**	**1944**	**RM$_m$**	**1797**	**1797**
gf(2^4)-mult [27]	*12*	*112*	*56*	*TODD*	*68*	**52**
gf(2^5)-mult [27]	*15*	*175*	*90*	*TODD*	*115*	**86**
gf(2^6)-mult [27]	*18*	*252*	*132*	*TODD*	*150*	**122**
gf(2^7)-mult [27]	*21*	*343*	*185*	*TODD*	*217*	**173**
gf(2^8)-mult [27]	*24*	*448*	*216*	*TODD*	*264*	**214**
ham15-low [3]	17	161	97	Tpar	97	97
ham15-med [3]	**17**	**574**	**230**	**Tpar**	**212**	**212**
ham15-high [3]	20	2457	1019	Tpar	1019	**1013**
hwb$_6$ [3]	7	105	75	Tpar	75	**72**
hwb$_8$ [3]	**12**	**5887**	**3531**	**RM$_{m\&r}$**	**3517**	**3501**
mod-mult-55 [27]	*9*	*49*	*28*	*TODD*	*35*	**20**
mod-red-21 [27]	11	119	73	Tpar	73	73
mod5$_4$ [27]	**5**	**28**	**16**	**Tpar**	**8**	**7**
nth-prime$_6$ [3]	**9**	**567**	**400**	**RM$_{m\&r}$**	**279**	**279**
nth-prime$_8$ [3]	*12*	*6671*	*4045*	*RM$_{m\&r}$*	*4047*	**3958**
qcla-adder$_{10}$ [27]	36	589	162	Tpar	162	**158**
qcla-com$_7$ [27]	*24*	*203*	*94*	*RM$_m$*	*95*	**91**
qcla-mod$_7$ [27]	26	413	235[a]	NRSCM	237	**216**
rc-adder$_6$ [27]	14	77	47	RM$_{m\&r}$	47	47
vbe-adder$_3$ [27]	10	70	24	Tpar	24	24

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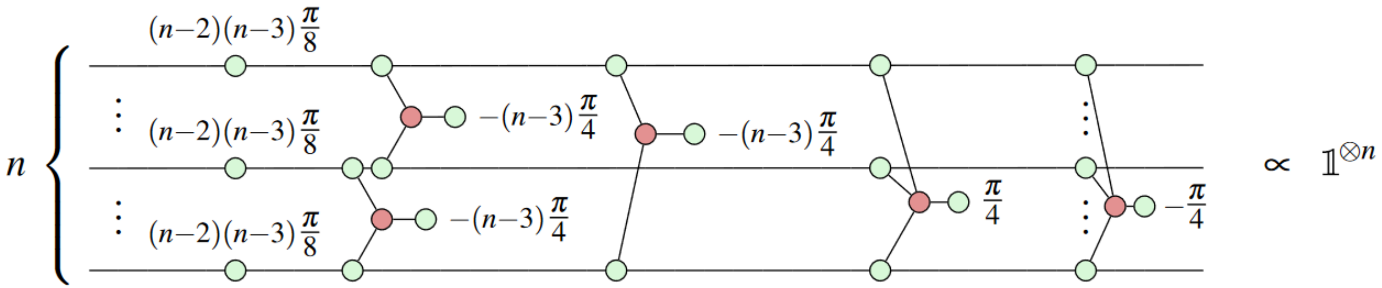

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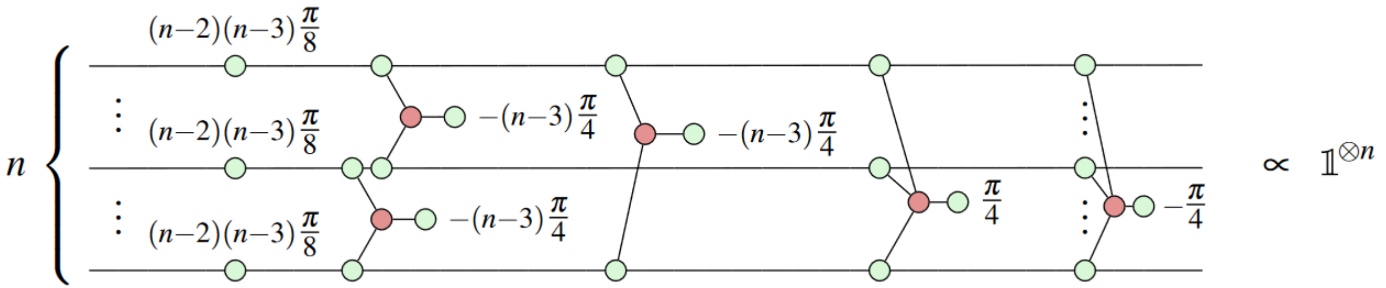
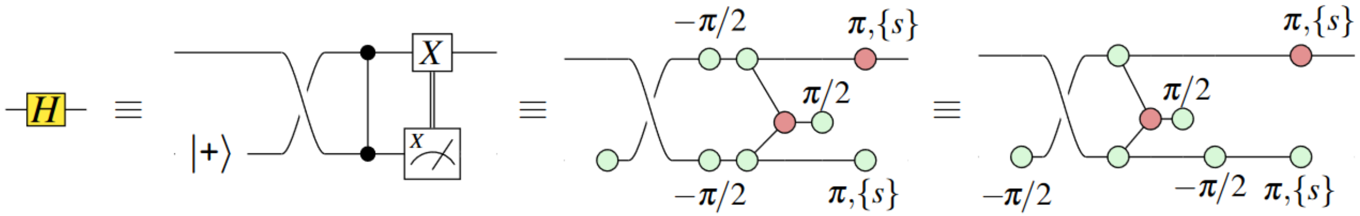
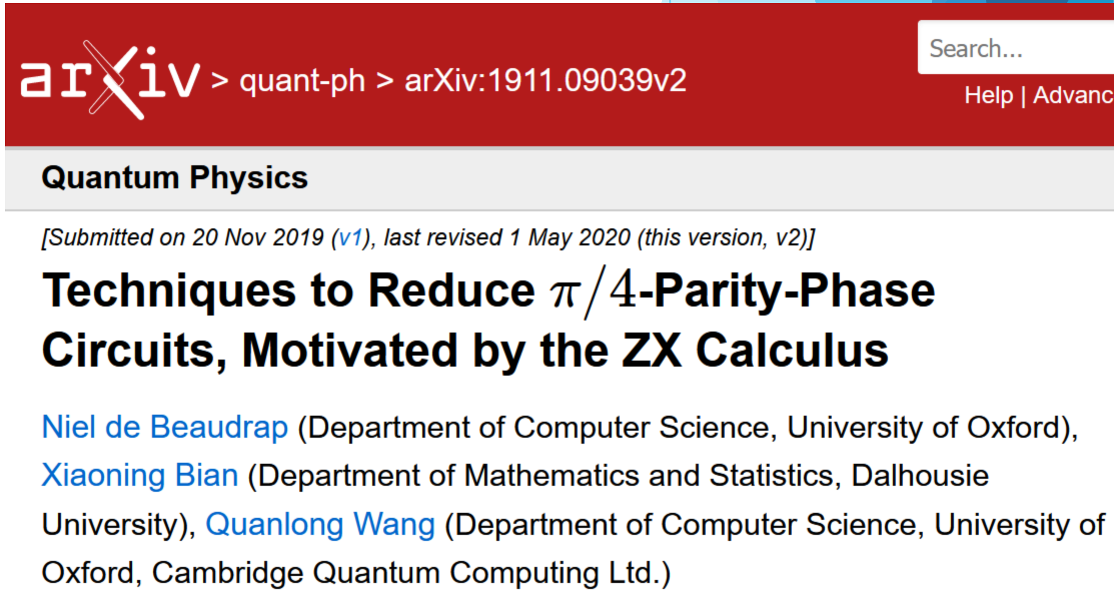
[Submitted on 20 Nov 2019 (v1), last revised 1 May 2020 (this version, v2)]

Techniques to Reduce $\pi/4$-Parity-Phase Circuits, Motivated by the ZX Calculus

Niel de Beaudrap (Department of Computer Science, University of Oxford), Xiaoning Bian (Department of Mathematics and Statistics, Dalhousie University), Quanlong Wang (Department of Computer Science, University of Oxford, Cambridge Quantum Computing Ltd.)







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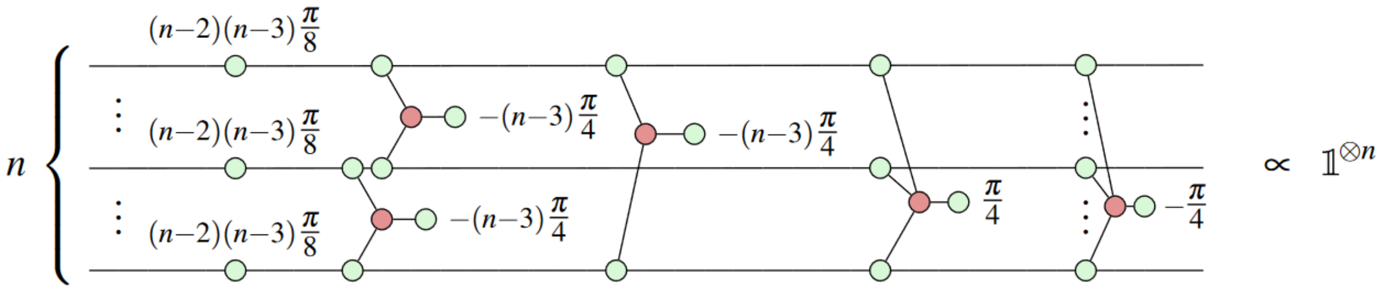

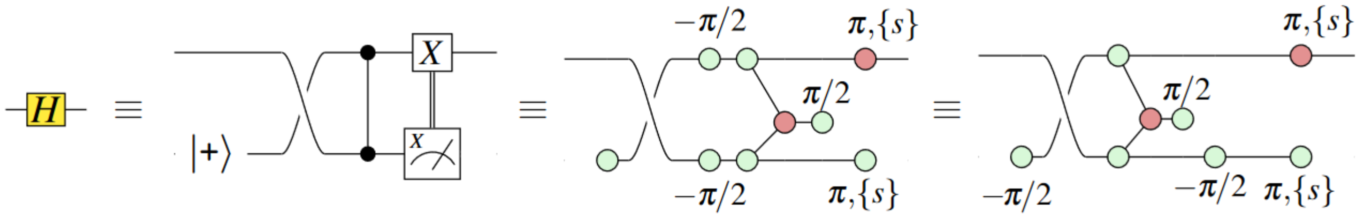

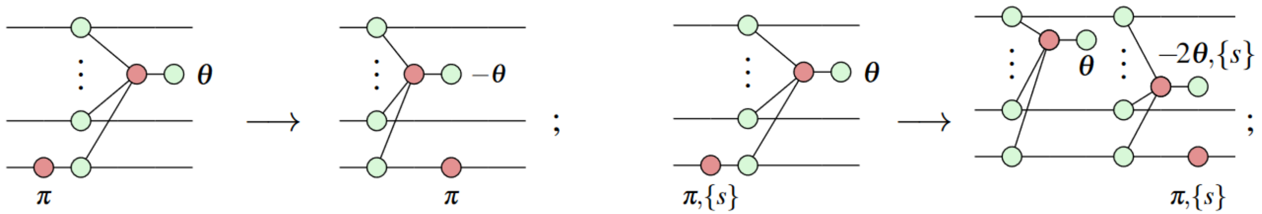

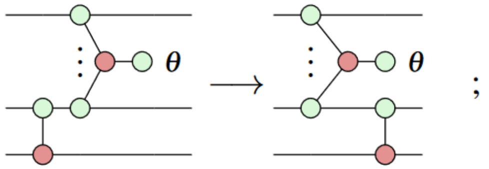

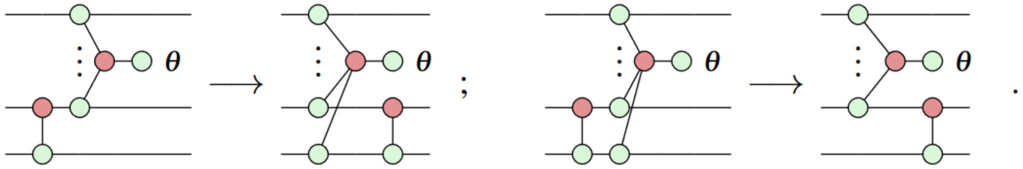

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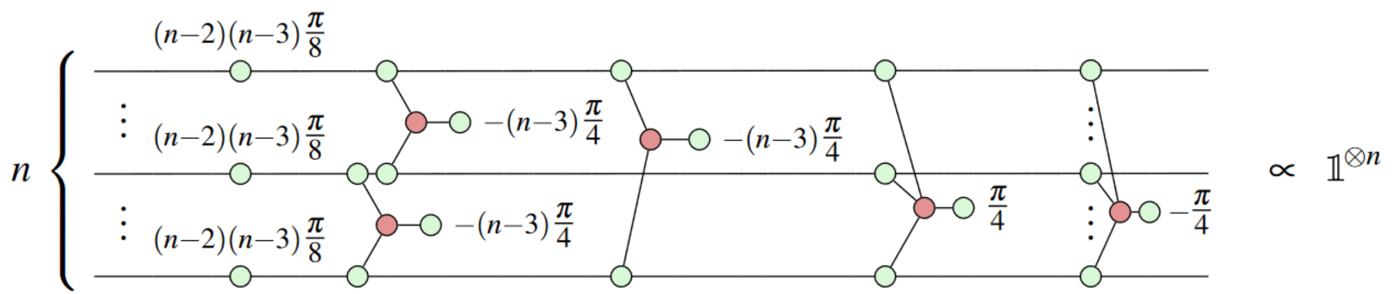

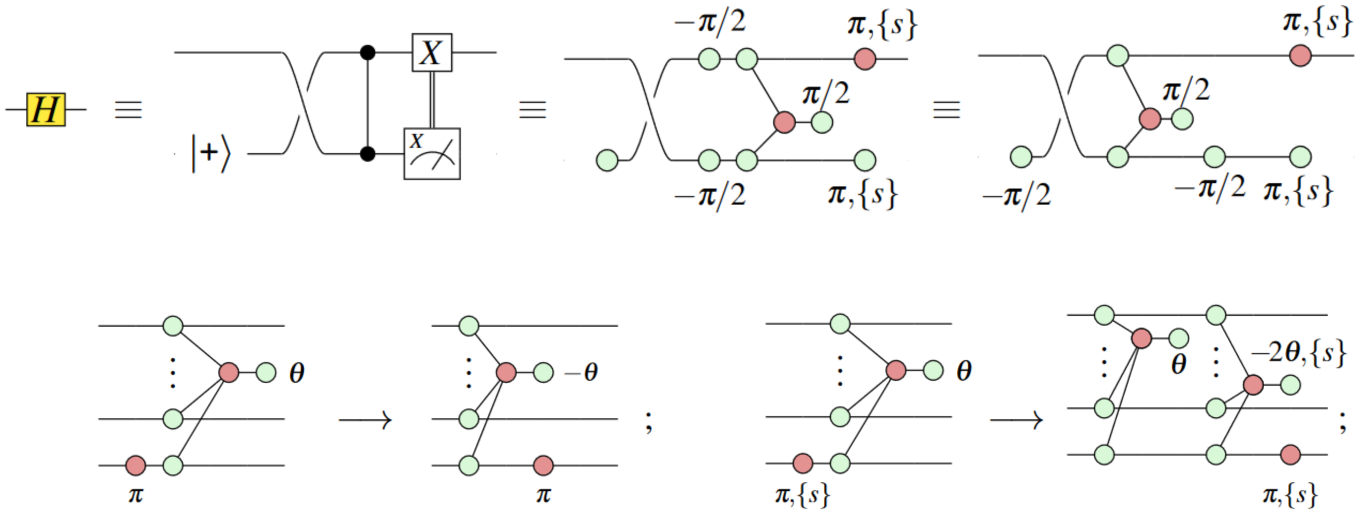

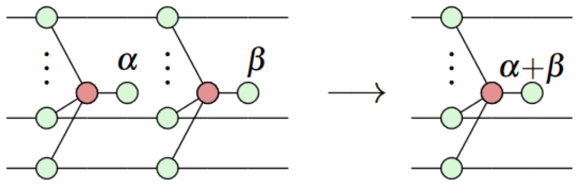

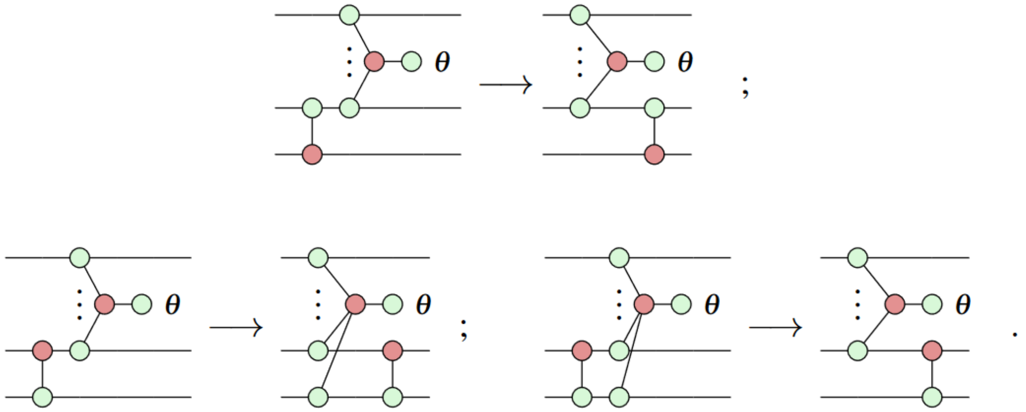

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Circuit	# qubits			T count & optimisation						
	n input	δn [23]	δn (ours)	init. #T	final #T (prev. opt.)	Ref.	time (s)	final #T (our results)	time (s)	Verified? (feynver)
Adder$_8$	24	71	41	399	212 (a)	[23]	227.81	**176** *	24.62	✓
Barenco Tof$_3$	5	3	3	28	14 (b)	[23]	0.01*	**13** *	0.07607	✓
Barenco Tof$_4$	7	7	7	56	24	[23]	0.45	25	1.884	✓
Barenco Tof$_5$	9	11	11	84	34	[23]	1.94	37	13.76	✓
Barenco Tof$_{10}$	19	31	31	224	84	[23]	460.33	97	24.49	✓
CSLA MUX$_3$	15	17	6	70	40 (b)	[23]	3.73	44	18.01	✓
CSUM MUX$_9$	30	12	12	196	74 (a)	[23]	36.57	84	23.98	✓
GF(2^4) Mult	12	7	0	112	56 (b)	[23]	0.55	**53** *	0.8180	✓
GF(2^5) Mult	15	9	0	175	90 (b)	[23]	6.96	**88** *	4.279	✓
GF(2^6) Mult	18	11	0	252	132 (b)	[23]	121.16	**128** *	7.894	✓
GF(2^7) Mult	21	13	0	343	185 (a)	[23]	153.75	**167** *	27.21	✓
GF(2^8) Mult	24	15	0	448	216 (a)	[23]	517.63	229	95.63	✓
GF(2^9) Mult	27	17	0	567	295	[23]	3213.53	306	24.79	✓
GF(2^{10}) Mult	30	19	0	700	351	[23]	23969.1	357	24.65	✓
GF(2^{16}) Mult	48	31	0	1 792	922	[23]	76312.5	972	25.65	✓ (d)
GF(2^{32}) Mult	96	–	0	7 168	4 128	[31]	1.834	**3 936** *	26.07	✓ (d)
GF(2^{64}) Mult	192	–	0	28 672	16 448	[31]	58.341	**15 865** *	29.73	–
GF(2^{128}) Mult	384	–	0	114 688	65 664	[31]	1744.746	**64 461** *	48.78	–
GF(2^{131}) Mult	393	–	0	120 127	69 037	[31]	1953.353	**67 772** *	53.39	–
GF(2^{163}) Mult	489	–	0	185 983	106 765	[31]	4955.927	**105 182** *	66.27	–
GF(2^{256}) Mult	768	–	0	458 752	–	–	–	**260 539** *	137.1	–
GF(2^{512}) Mult	1536	–	0	1 835 008	–	–	–	**1 046 964** *	850.7 (d)	–
Mod5$_4$	5	6	0	28	16 (b)	[31]	0.001*	**7** *	0.00899	✓
Mod Adder$_{1024}$	28	$\leqslant$ 270 (c)	304	1 995	978	[23]	665.5	1 010	27.56	✓ (d)
Mod Mult$_{55}$	9	10	3	49	28 (a)	[23]	0.02	**19** *	0.5775	✓
Mod Red$_{21}$	11	17	17	119	69 (b)	[23]	0.59	**65**	27.68	✓
QCLA Adder$_{10}$	36	28	25	238	157	[23]	366.1	**147** *	24.96	✓
QCLA Com$_7$	24	19	18	203	81	[23]	170.77	84	24.21	✓
QCLA Mod$_7$	26	58	58	413	221 (a)	[23]	289.77	233	24.26	✓ (d)
RC Adder$_6$	14	21	10	77	45 (b)	[23]	0.97	**38**	30.70	✓
NC Toff$_3$	5	2	2	21	13	[23]	0.01*	**13** *	0.04005	✓
NC Toff$_4$	7	4	4	35	19	[23]	0.06	**19** *	0.5322	✓
NC Toff$_5$	9	11	6	49	25	[23]	0.4	26	2.910	✓
NC Toff$_{10}$	19	16	16	119	55	[23]	44.78	60	28.01	✓
VBE Adder$_3$	10	4	4	70	20	[23]	0.15	**20** *	1.896	✓

arXiv > quant-ph > arXiv:1911.09039v2

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Quantum Physics

[Submitted on 20 Nov 2019 (v1), last revised 1 May 2020 (this version, v2)]

Techniques to Reduce $\pi/4$-Parity-Phase Circuits, Motivated by the ZX Calculus

Niel de Beaudrap (Department of Computer Science, University of Oxford), Xiaoning Bian (Department of Mathematics and Statistics, Dalhousie University), Quanlong Wang (Department of Computer Science, University of Oxford, Cambridge Quantum Computing Ltd.)

arXiv > quant-ph > arXiv:2004.05164

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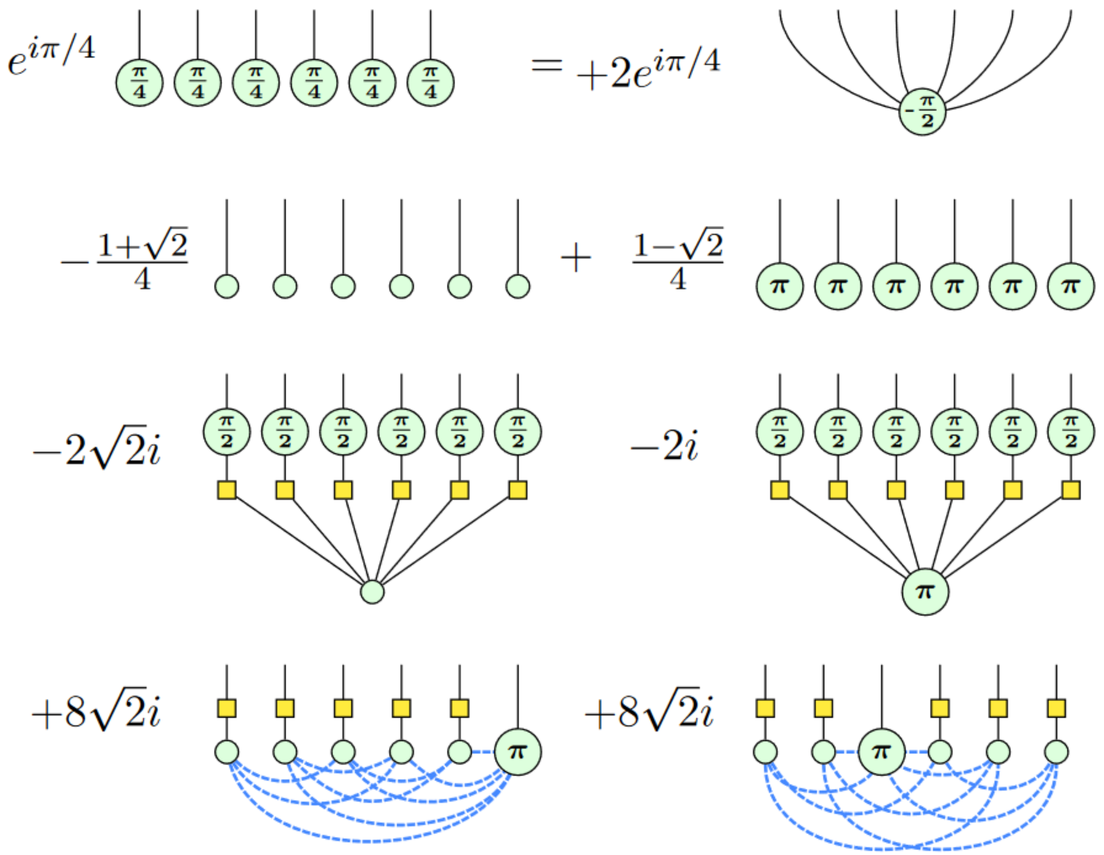
Quantum Physics

[Submitted on 10 Apr 2020 (v1), last revised 14 Apr 2020 (this version, v2)]

Fast and effective techniques for T-count reduction via spider nest identities

Niel de Beaudrap, Xiaoning Bian, Quanlong Wang

Simulation Techniques



$e^{i\pi/4}$
$\frac{\pi}{4}$ $\frac{\pi}{4}$ $\frac{\pi}{4}$ $\frac{\pi}{4}$ $\frac{\pi}{4}$ $\frac{\pi}{4}$
$= +2e^{i\pi/4}$
$-\frac{\pi}{2}$
$-\frac{1+\sqrt{2}}{4}$
$+\frac{1-\sqrt{2}}{4}$
π π π π π π
$-2\sqrt{2}i$
$\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$
$-2i$
$\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$ $\frac{\pi}{2}$
π
$+8\sqrt{2}i$
π
$+8\sqrt{2}i$
π

arXiv > quant-ph > arXiv:2109.01076
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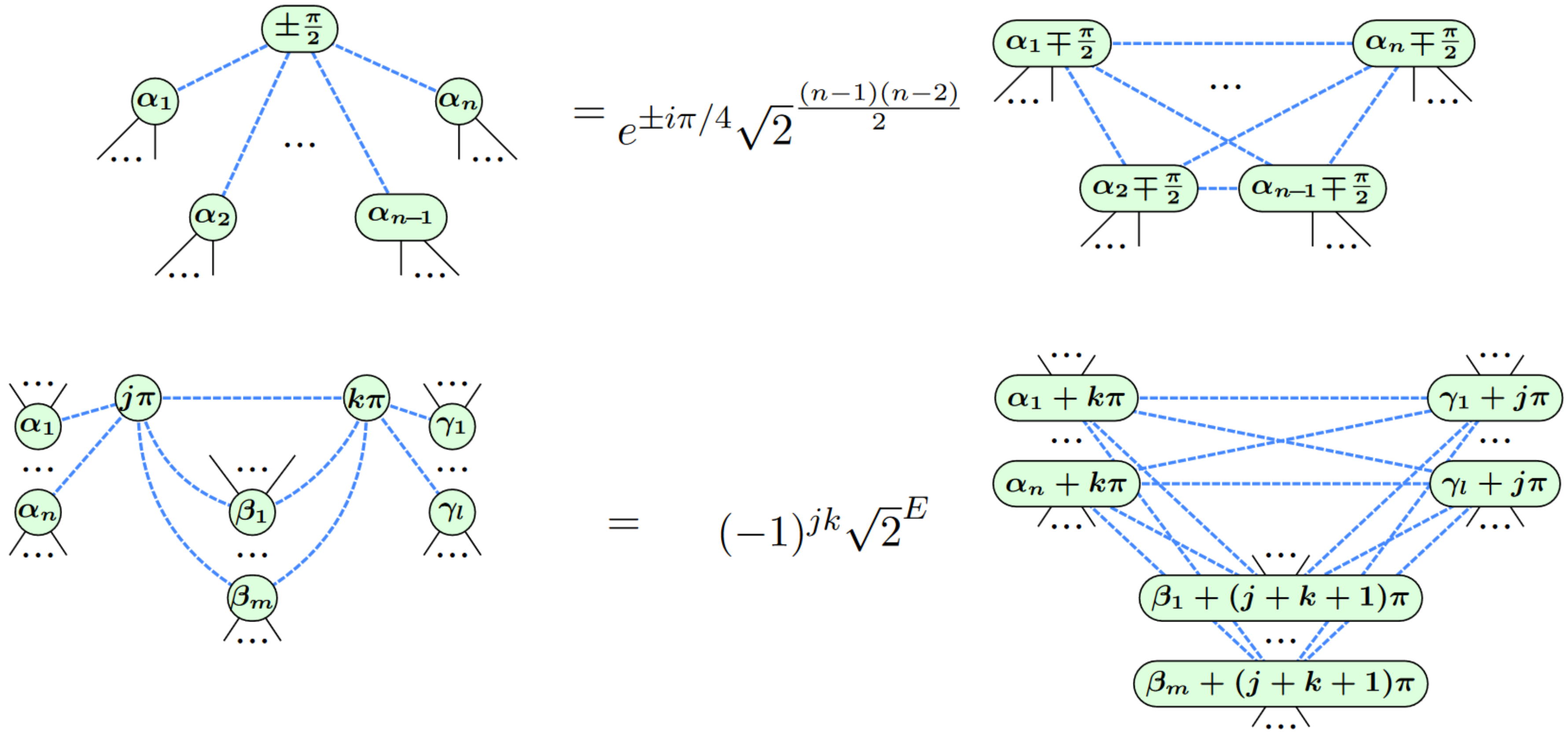
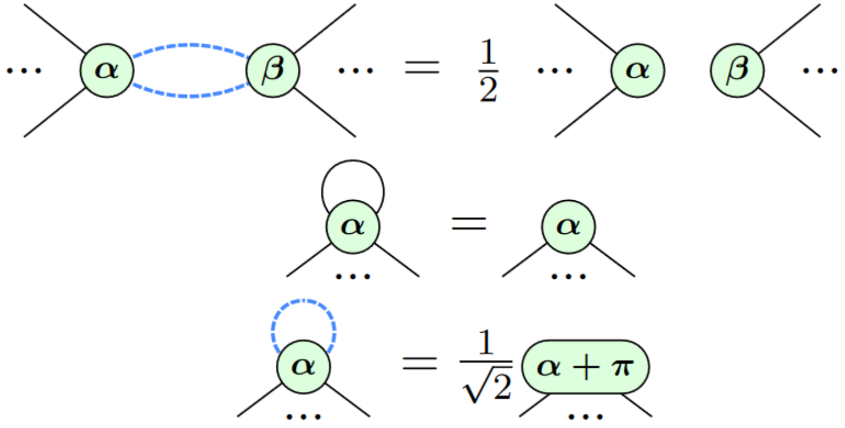
[Submitted on 2 Sep 2021]
Simulating quantum circuits with ZX-calculus reduced stabiliser decompositions
Aleks Kissinger, John van de Wetering


$= e^{\pm i\pi/4}\sqrt{2}^{\frac{(n-1)(n-2)}{2}}$
$= (-1)^{jk}\sqrt{2}^{E}$


$= \frac{1}{2}$
$=$
$= \frac{1}{\sqrt{2}}$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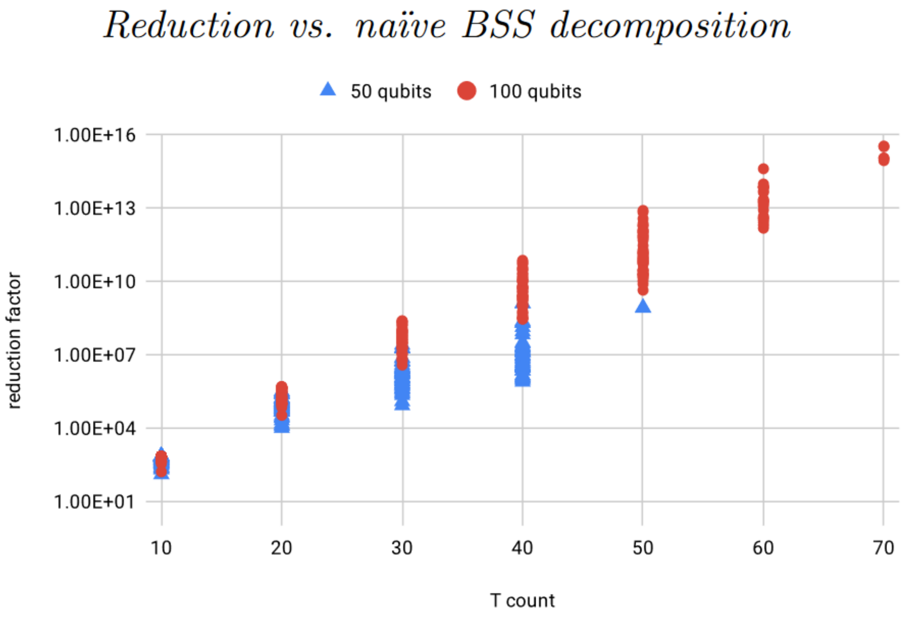
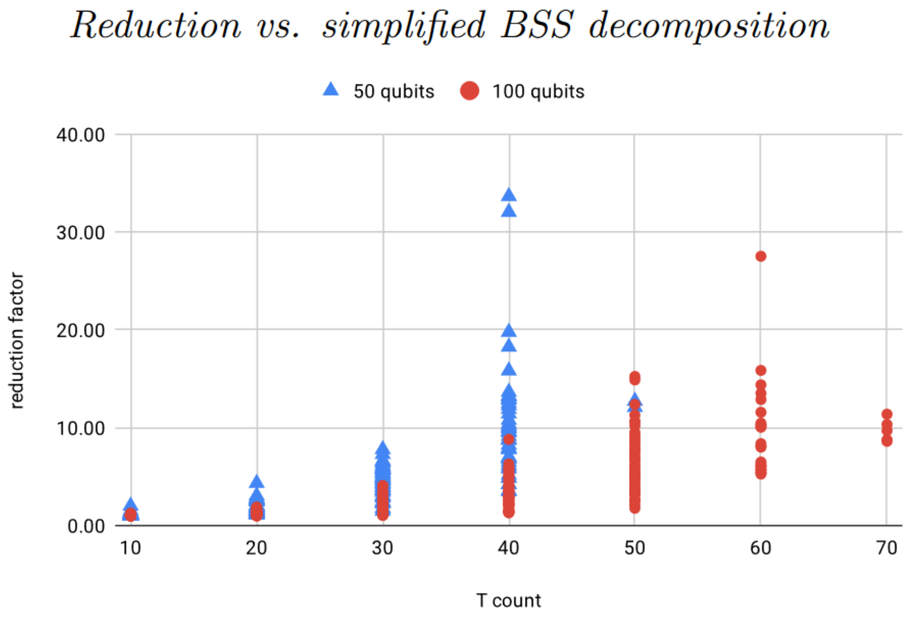
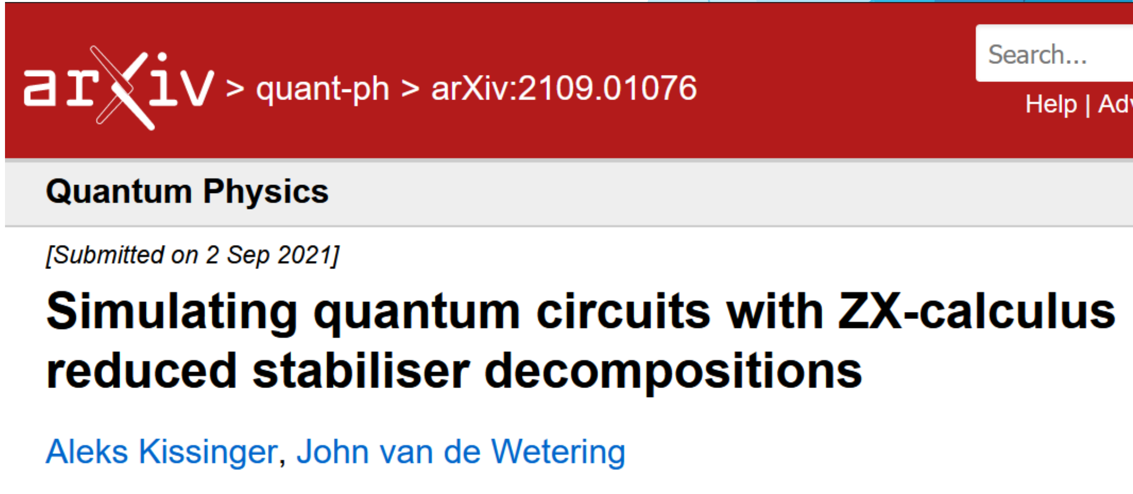


Reduction vs. naïve BSS decomposition
50 qubits
100 qubits
1.00E+16
1.00E+13
1.00E+10
1.00E+07
1.00E+04
1.00E+01
reduction factor
10
20
30
40
50
60
70
T count



Reduction vs. simplified BSS decomposition
50 qubits
100 qubits
40.00
30.00
20.00
10.00
0.00
reduction factor
10
20
30
40
50
60
70
T count



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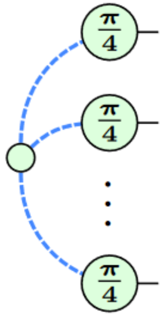
$$|\mathrm{cat}_n\rangle = \frac{1}{\sqrt{2}}$$

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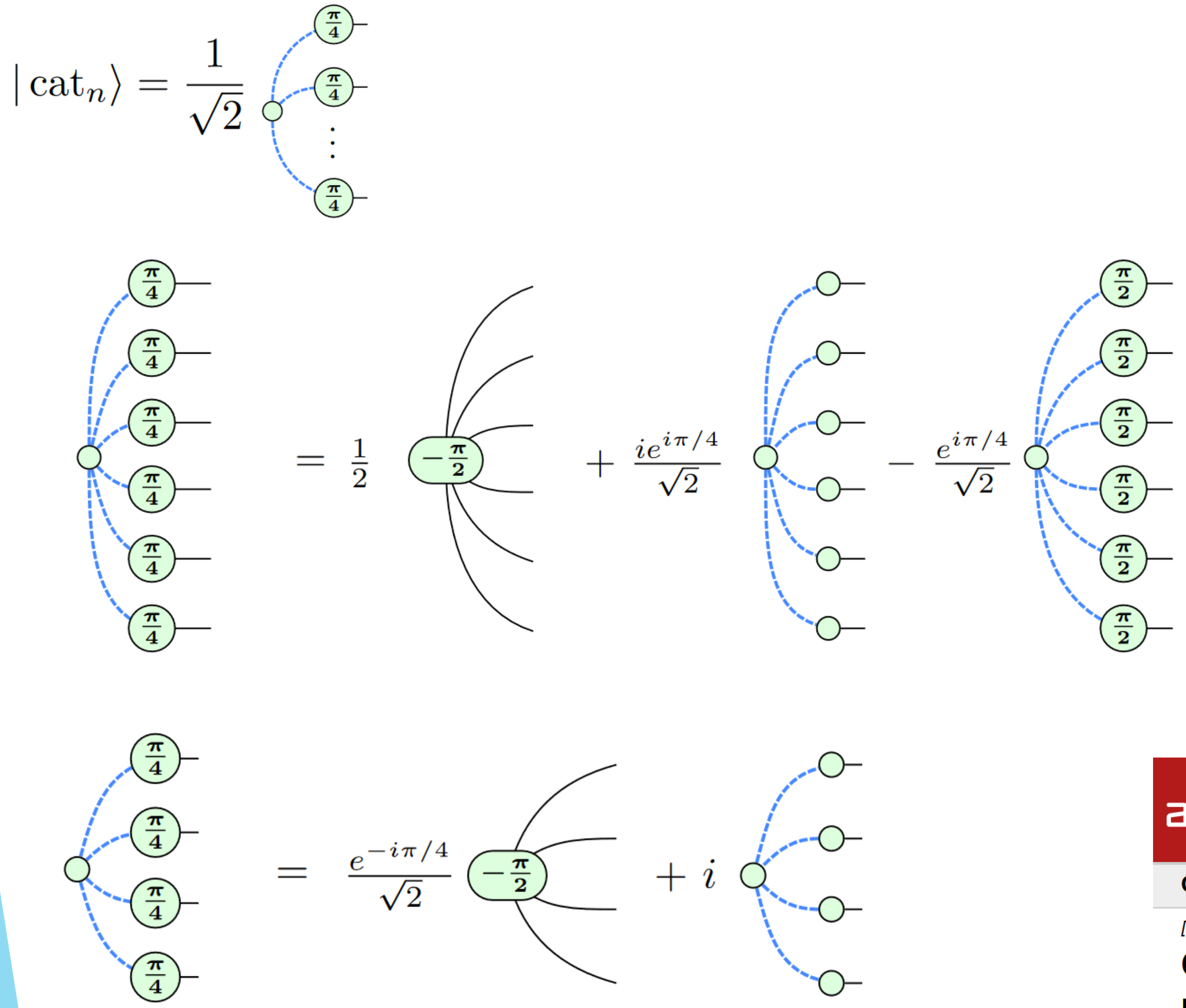
[Submitted on 18 Feb 2022]

Classical simulation of quantum circuits with partial and graphical stabiliser decompositions

Aleks Kissinger, John van de Wetering, Renaud Vilmart



|cat_n⟩ = 1/√2
= 1/2
+ ie^{iπ/4}/√2
− e^{iπ/4}/√2
= e^{−iπ/4}/√2
+ i

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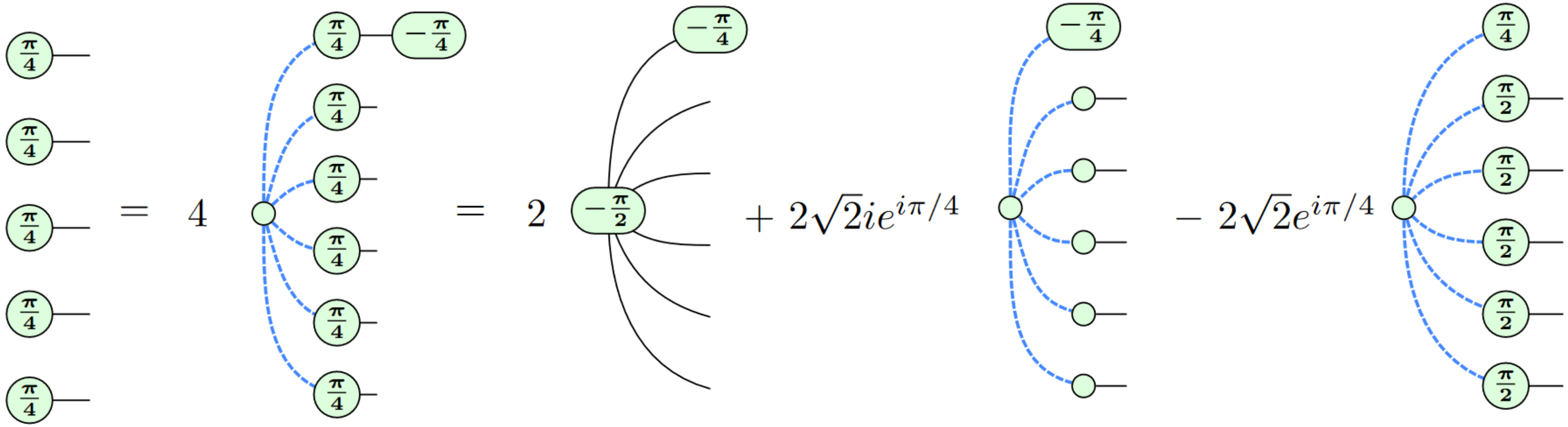
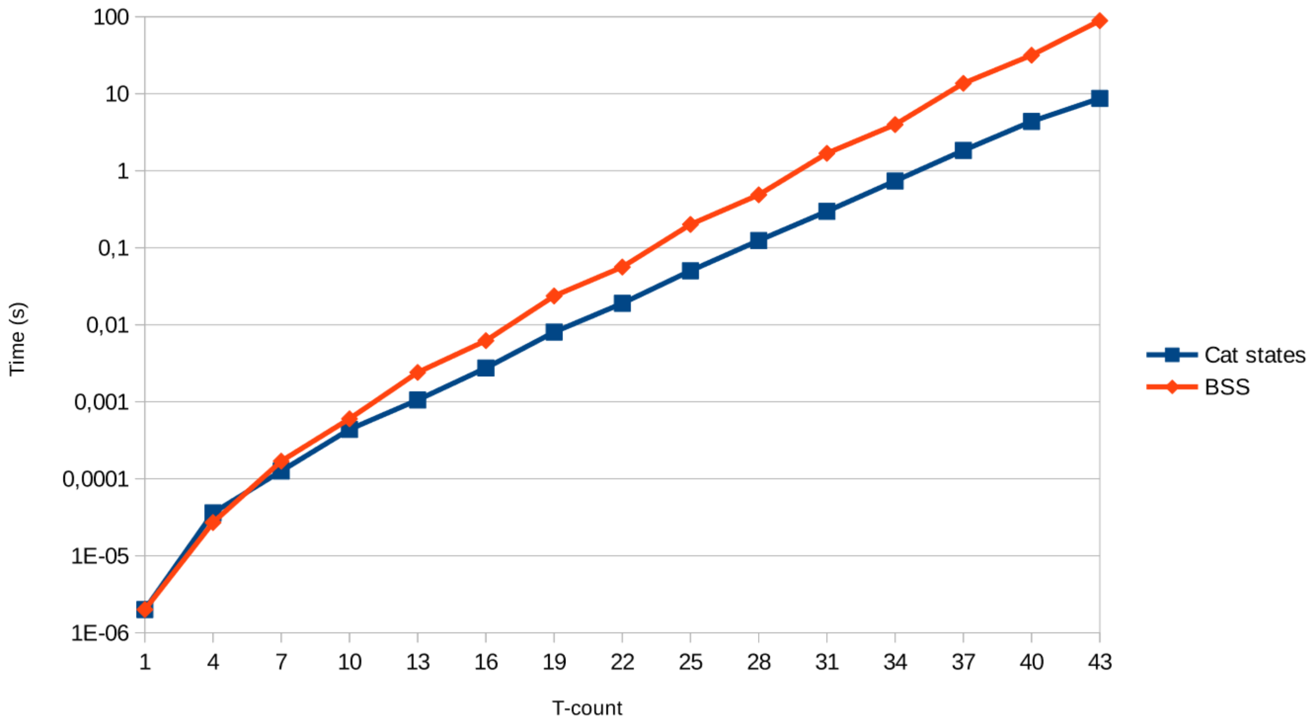

= 4
= 2
$+ 2\sqrt{2}ie^{i\pi/4}$
$- 2\sqrt{2}e^{i\pi/4}$


Time (s)
100
10
1
0,1
0,01
0,001
0,0001
1E-05
1E-06
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43
T-count
Cat states
BSS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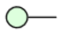
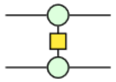
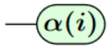
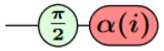
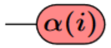
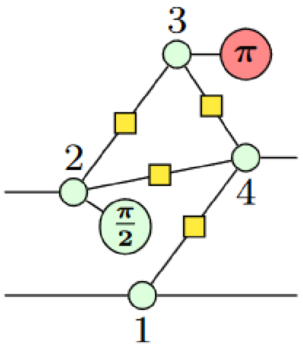
Circuit Extraction Techniques

operator	N_i	E_{ij}	$\langle +_{\mathrm{XY},\alpha(i)} \vert_i$	$\langle +_{\mathrm{XZ},\alpha(i)} \vert_i$	$\langle +_{\mathrm{YZ},\alpha(i)} \vert_i$
diagram					

Example 2.15. The measurement pattern with the qubit register $V = \{1, 2, 3, 4\}$, input and output sets $I = \{1, 2\}$ and $O = \{1, 4\}$ and the sequence of commands

$$M_2^{\mathrm{XY},\frac{\pi}{2}} M_3^{\mathrm{YZ},\pi} E_{14} E_{23} E_{24} E_{34} N_3 N_4$$

is represented by the following ZX-diagram:



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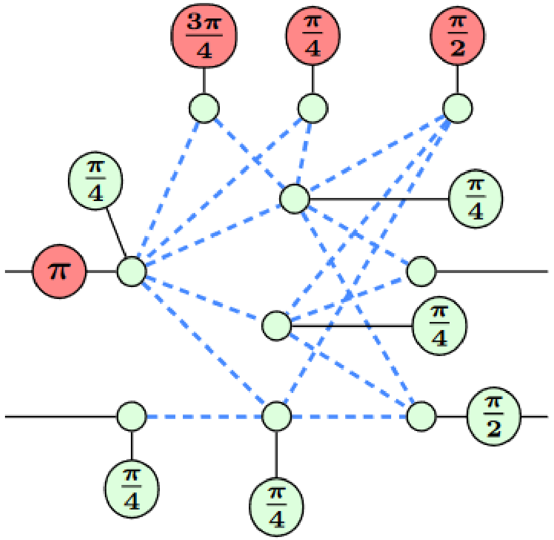
Quantum Physics

[Submitted on 3 Mar 2020 (v1), last revised 23 Mar 2021 (this version, v3)]

There and back again: A circuit extraction tale

Miriam Backens, Hector Miller-Bakewell, Giovanni de Felice, Leo Lobski, John van de Wetering

operator	N_i	E_{ij}	$\langle +_{XY,\alpha(i)} \rvert_i$	$\langle +_{XZ,\alpha(i)} \rvert_i$	$\langle +_{YZ,\alpha(i)} \rvert_i$
diagram					



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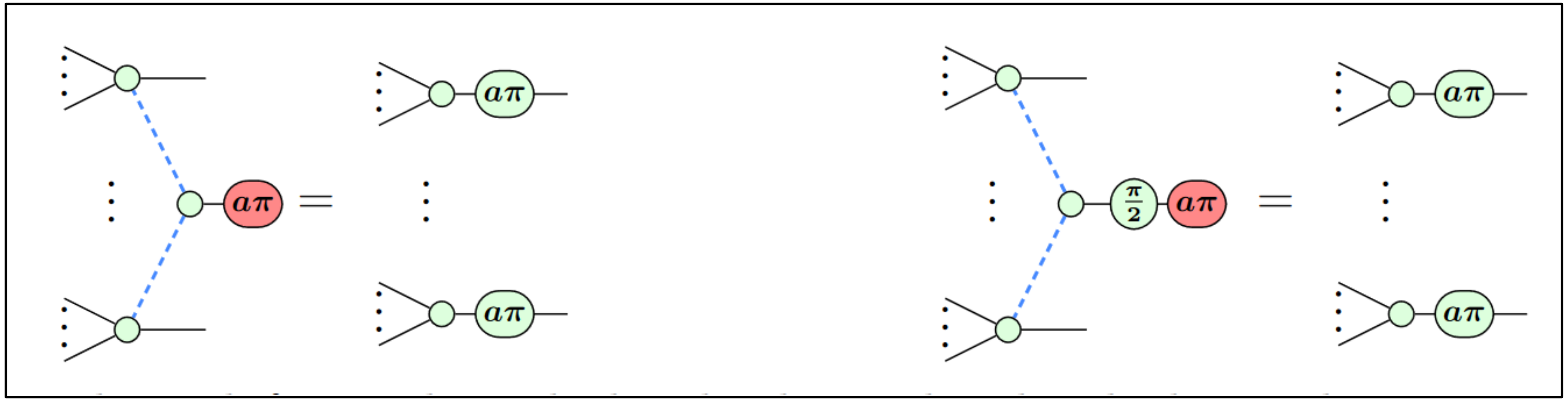

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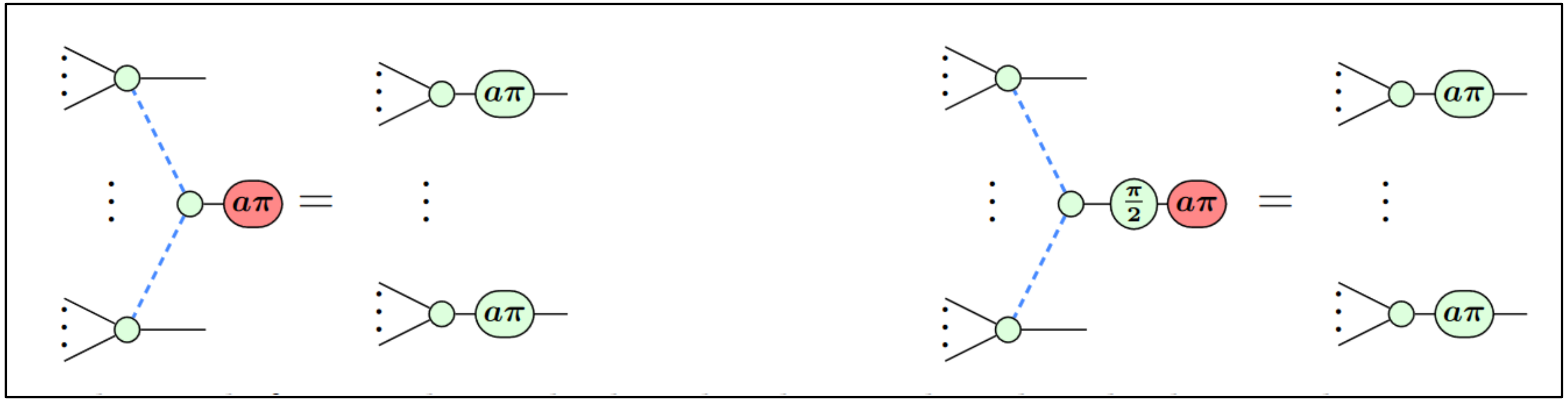

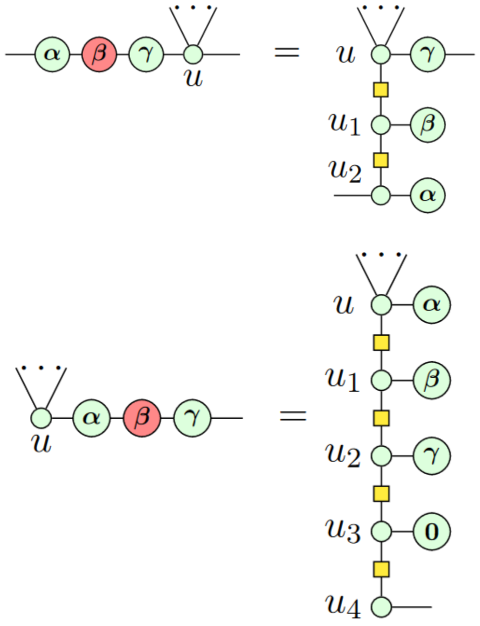

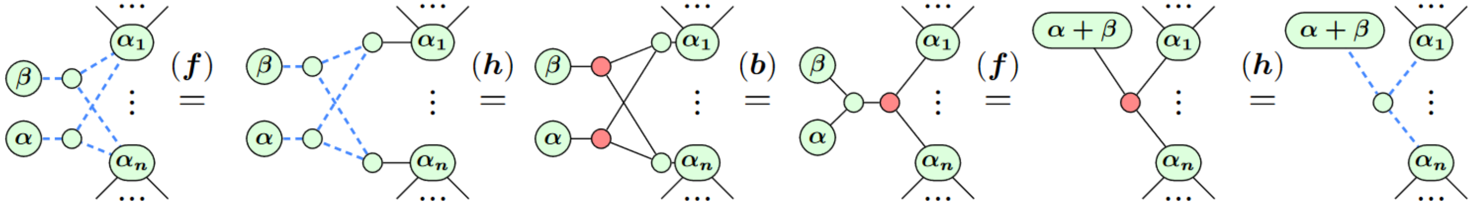

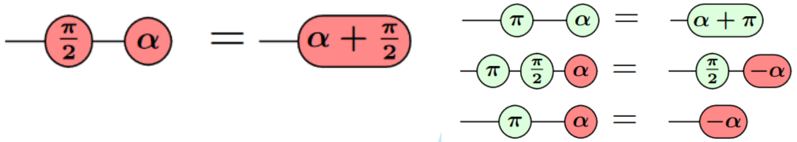

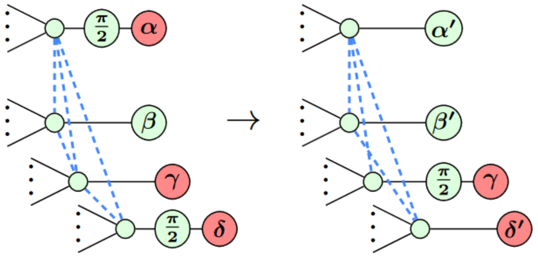

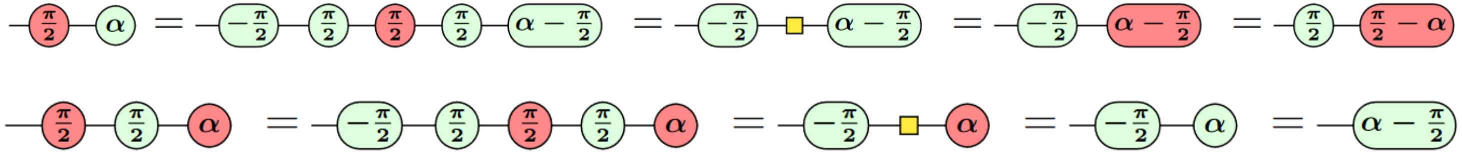

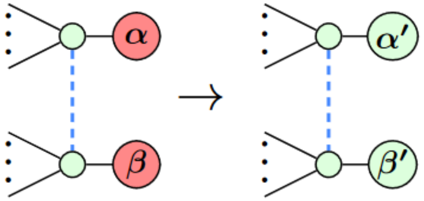

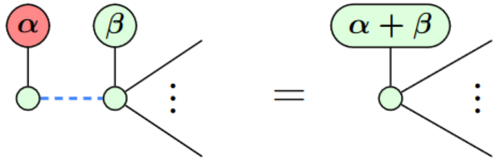

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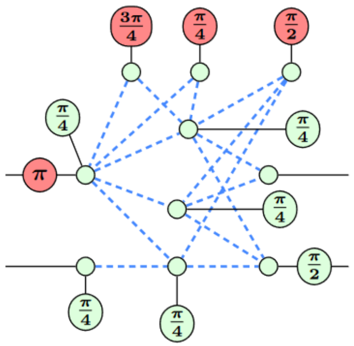
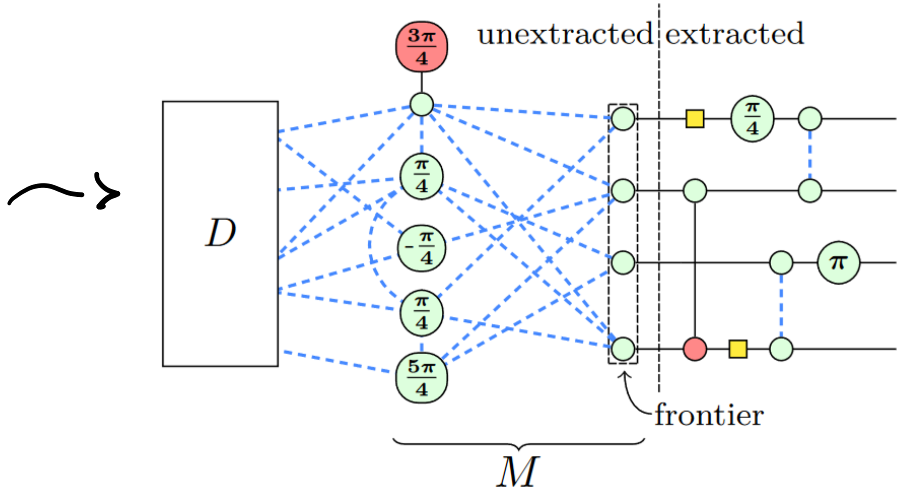
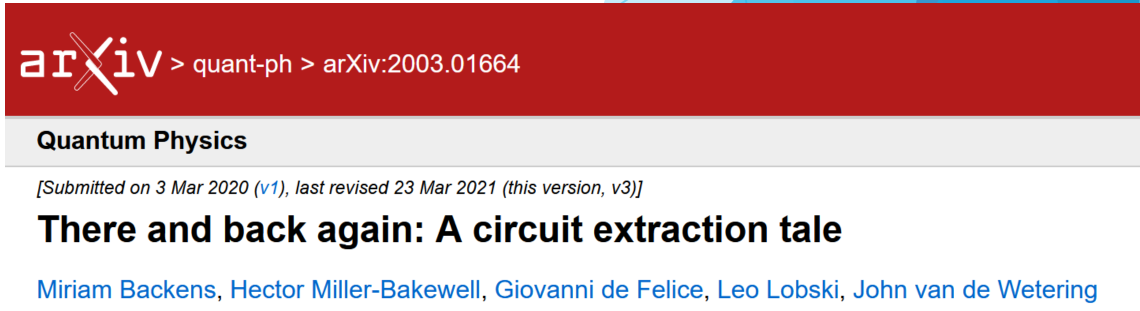




unextracted
extracted
D
frontier
M



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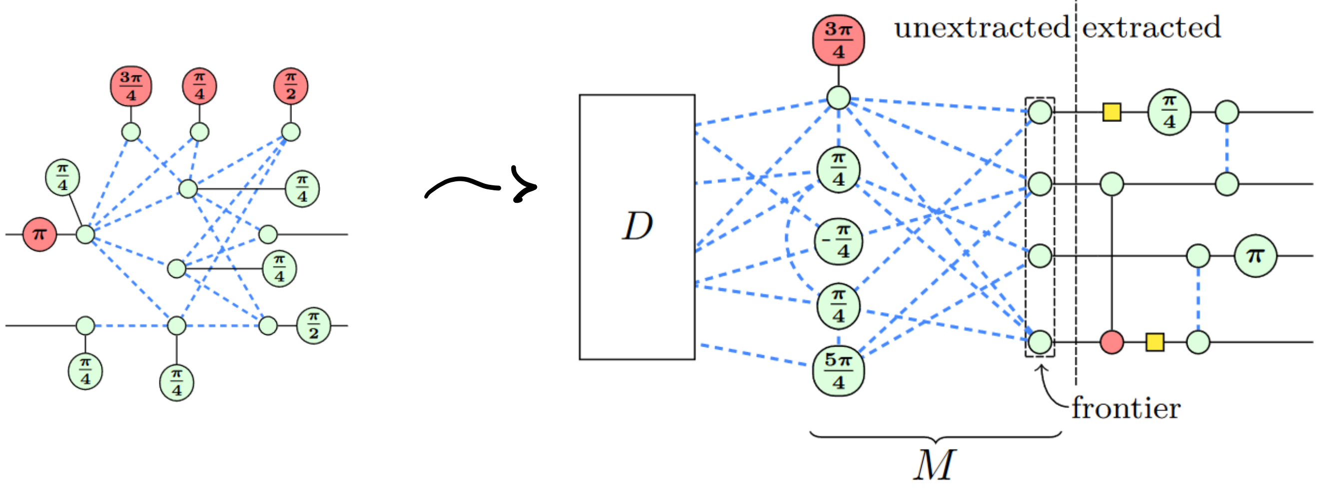

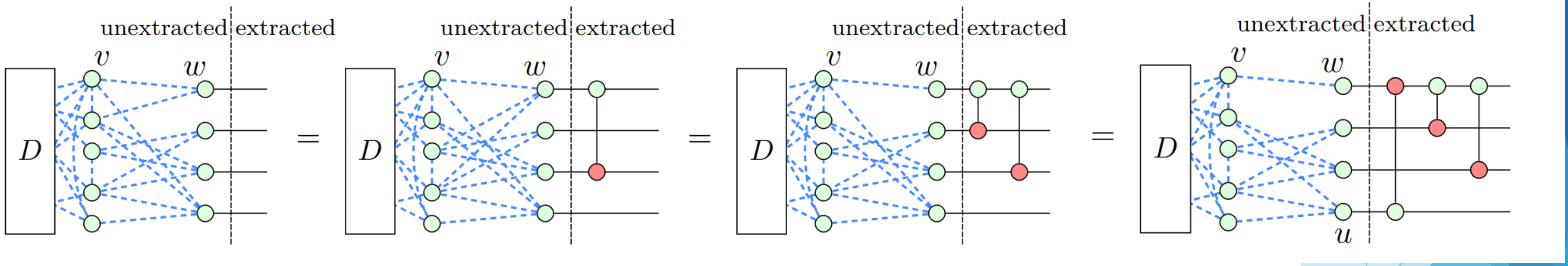

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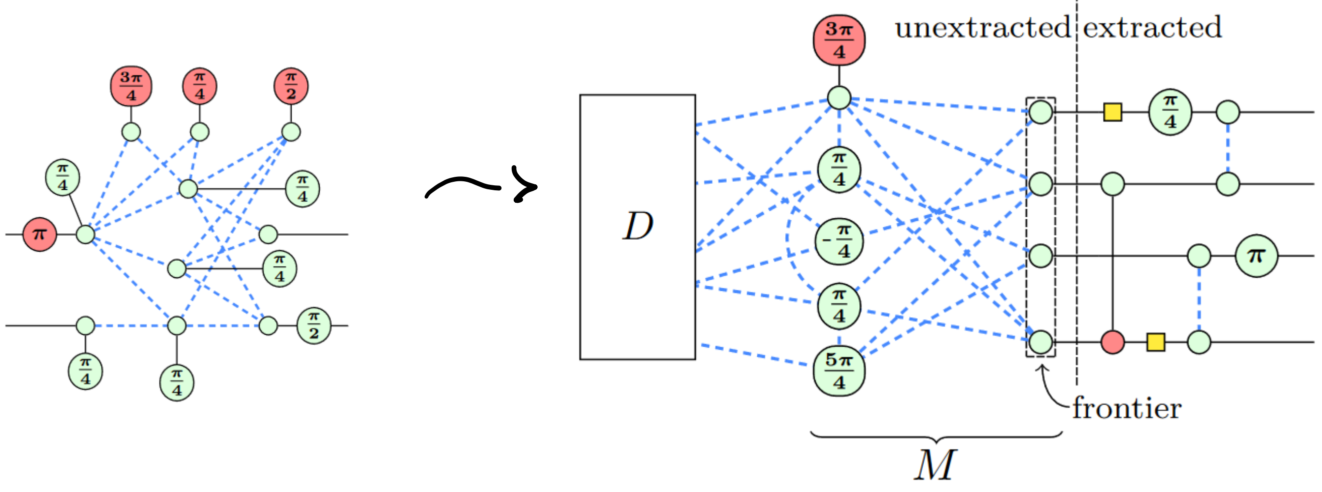

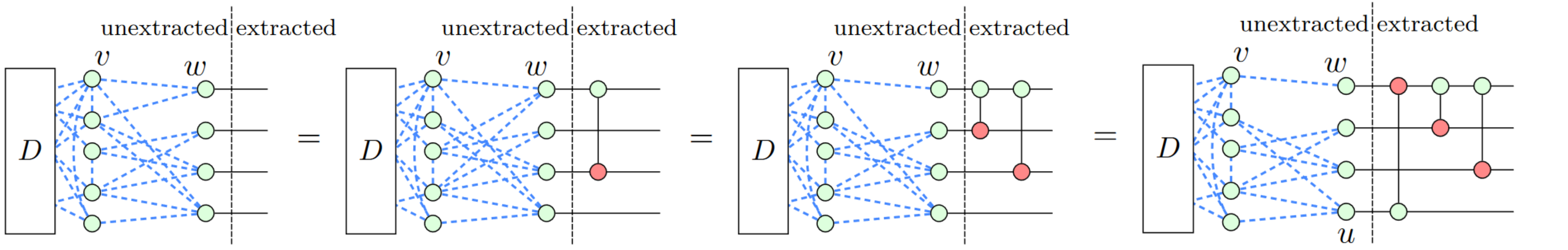

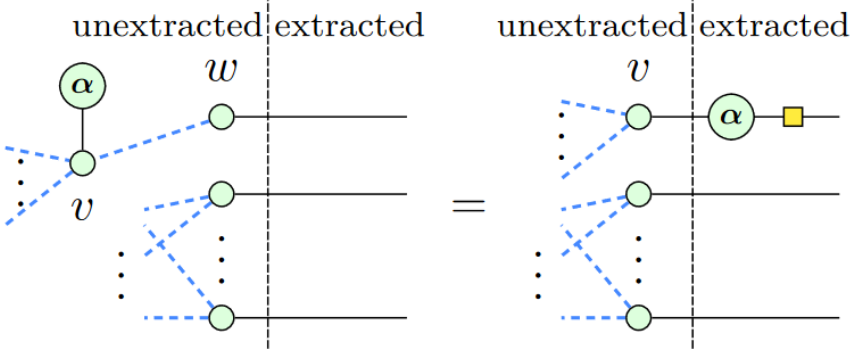

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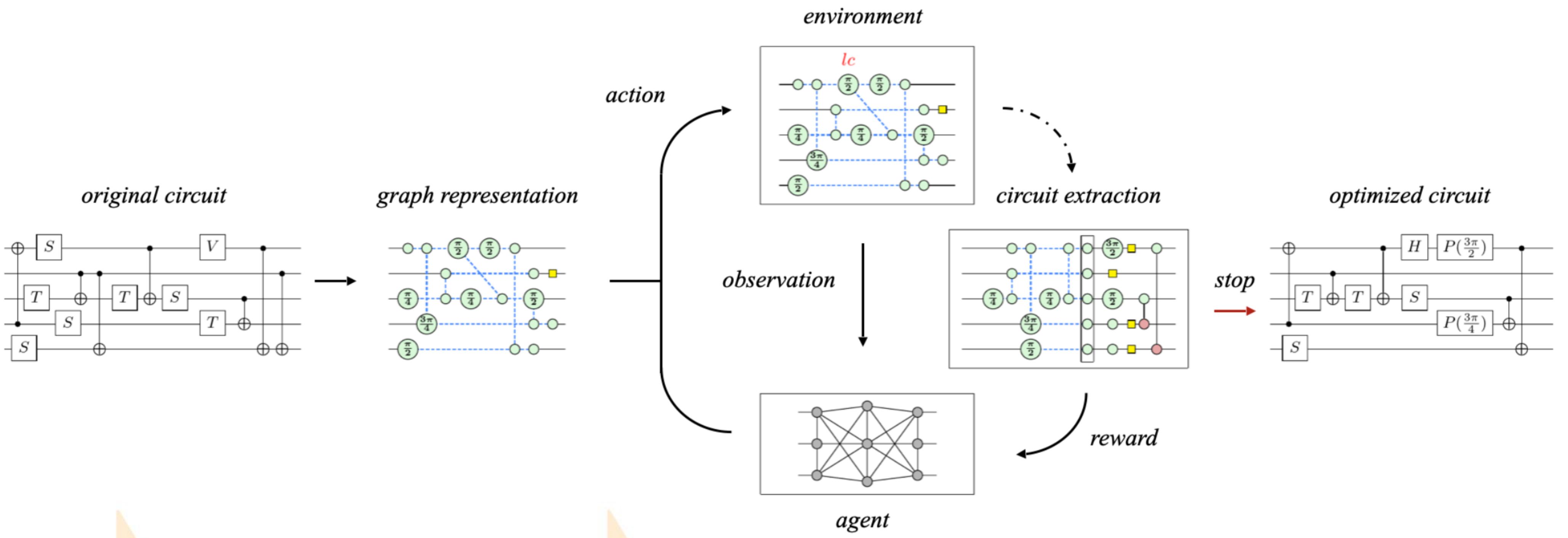

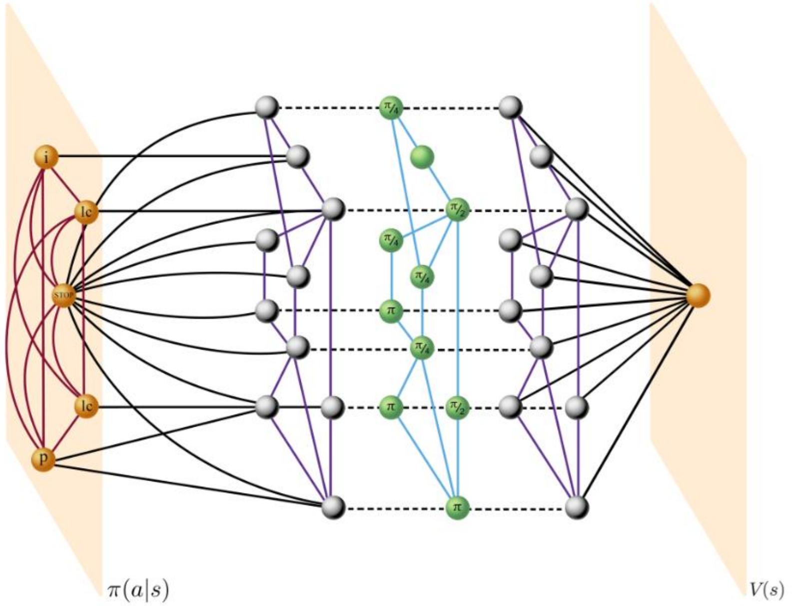

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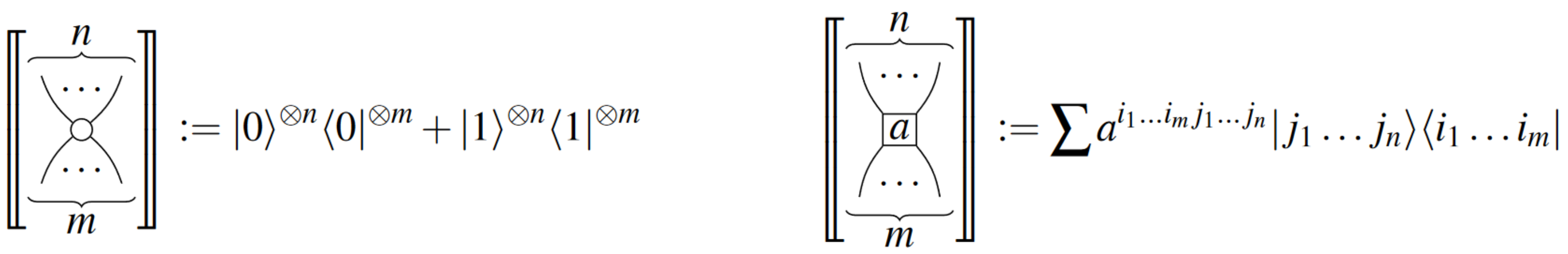
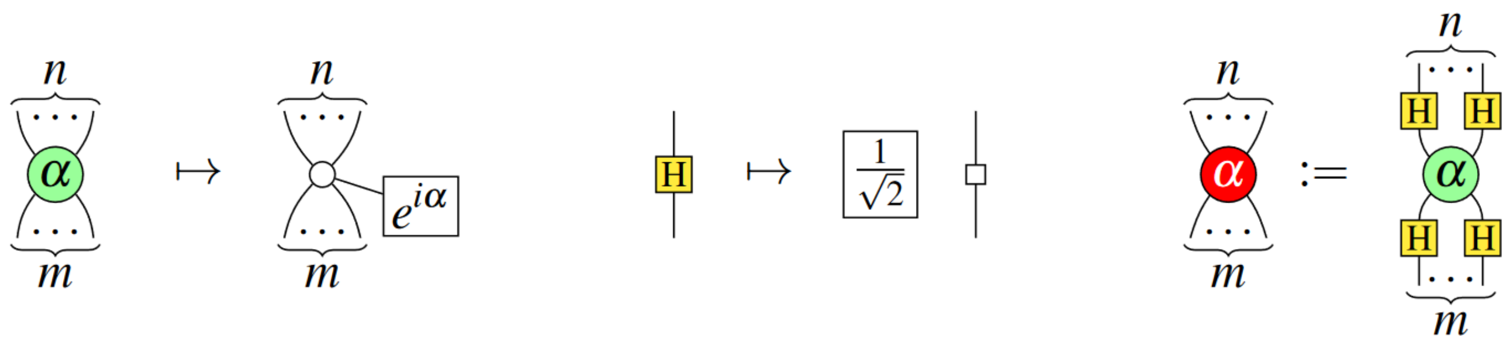
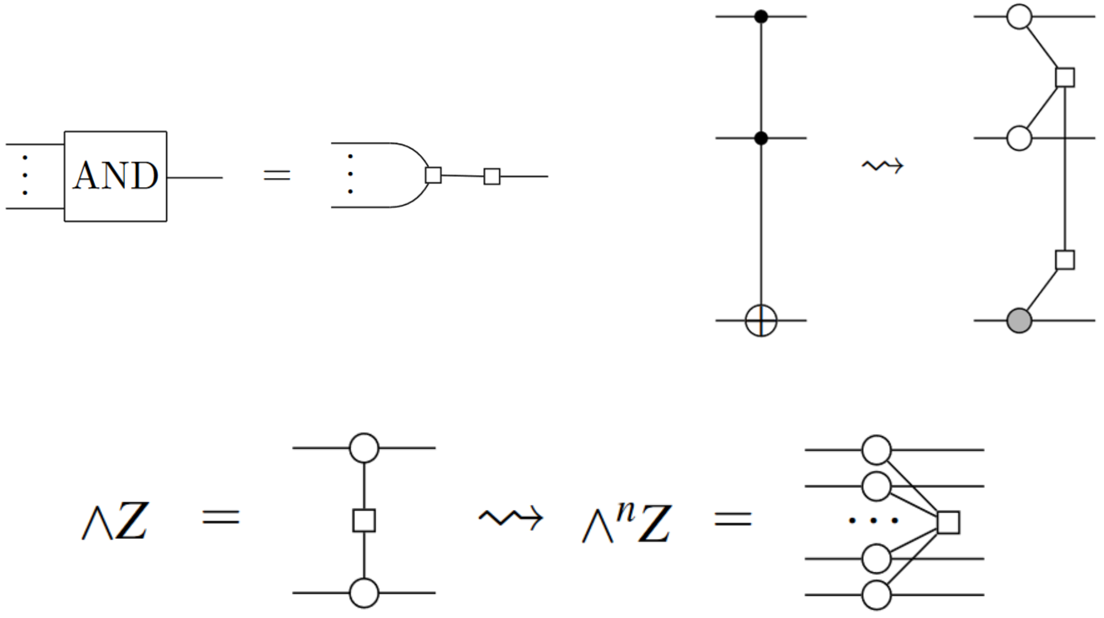
Reinforcement Learning Based Quantum Circuit Optimization via ZX-Calculus

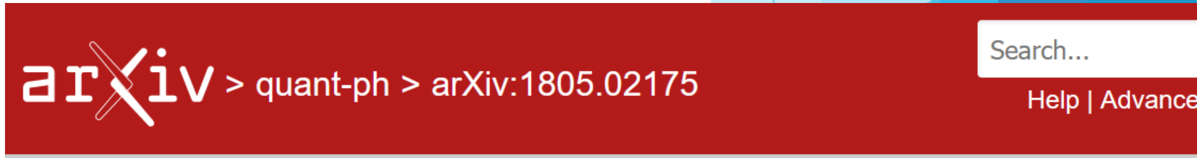
Jordi Riu, Jan Nogué, Gerard Vilaplana, Artur Garcia-Saez, Marta P. Estarellas

The ZH and ZX& Calculi







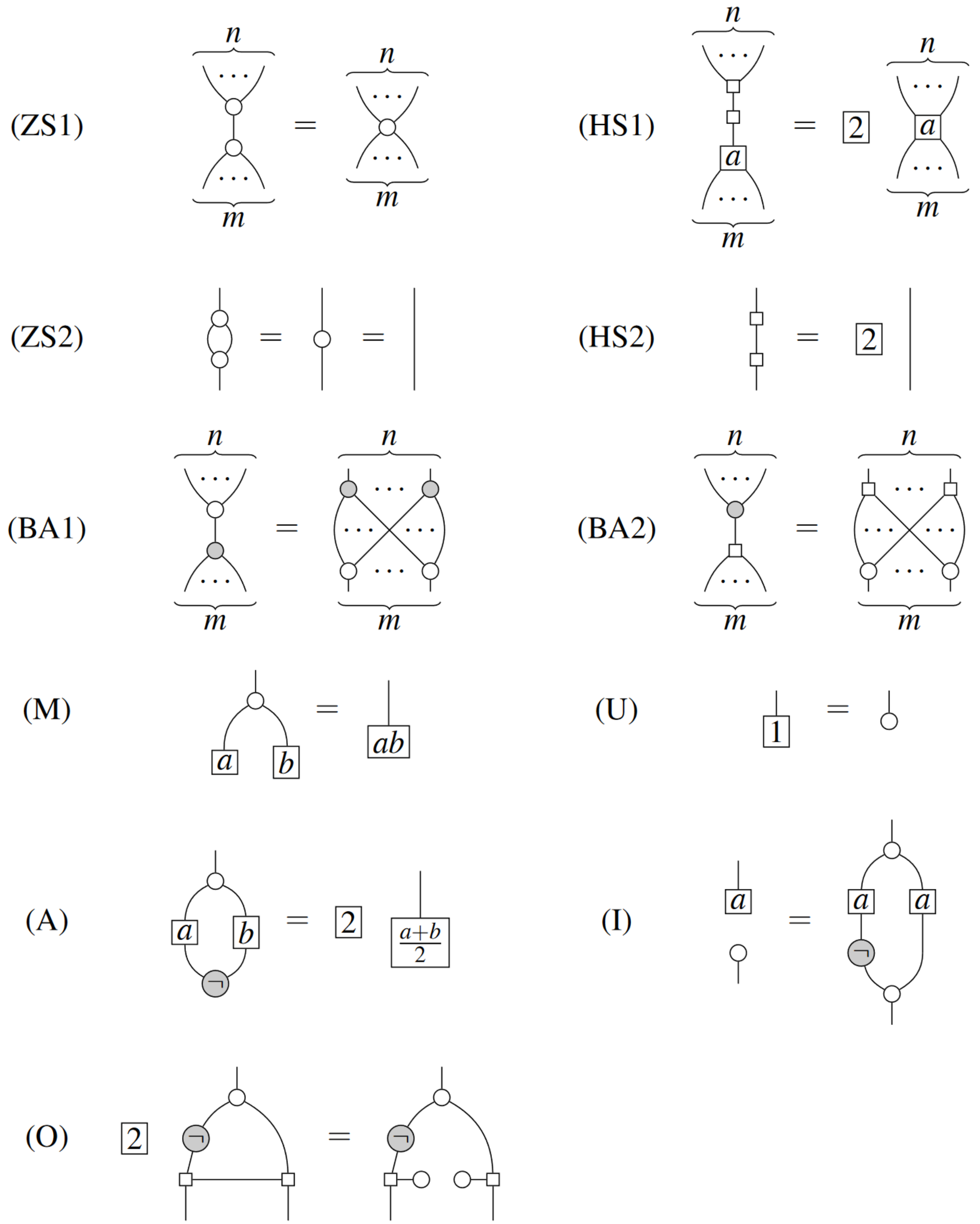


Quantum Physics

[Submitted on 6 May 2018 (v1), last revised 29 Jan 2019 (this version, v2)]

ZH: A Complete Graphical Calculus for Quantum Computations Involving Classical Non-linearity

Miriam Backens, Aleks Kissinger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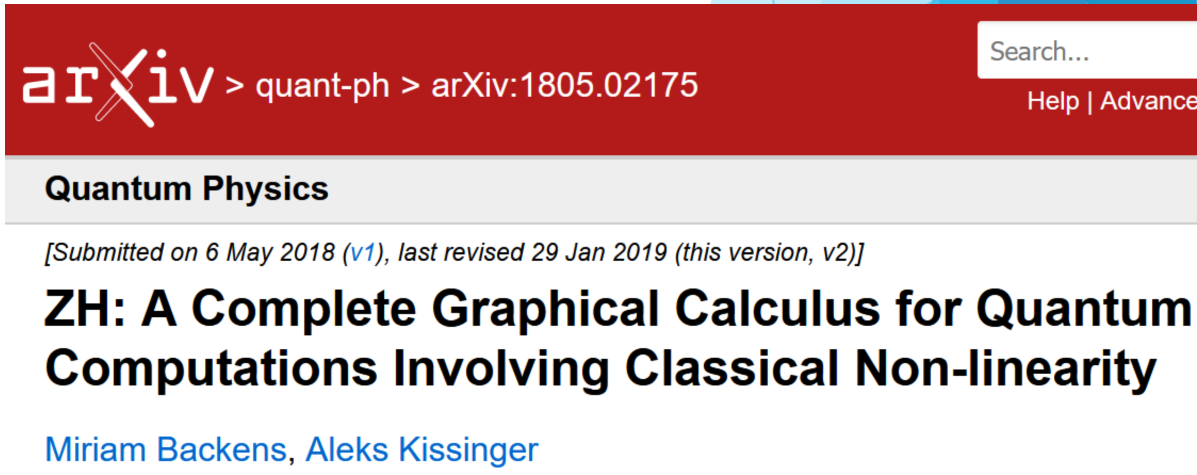
(O)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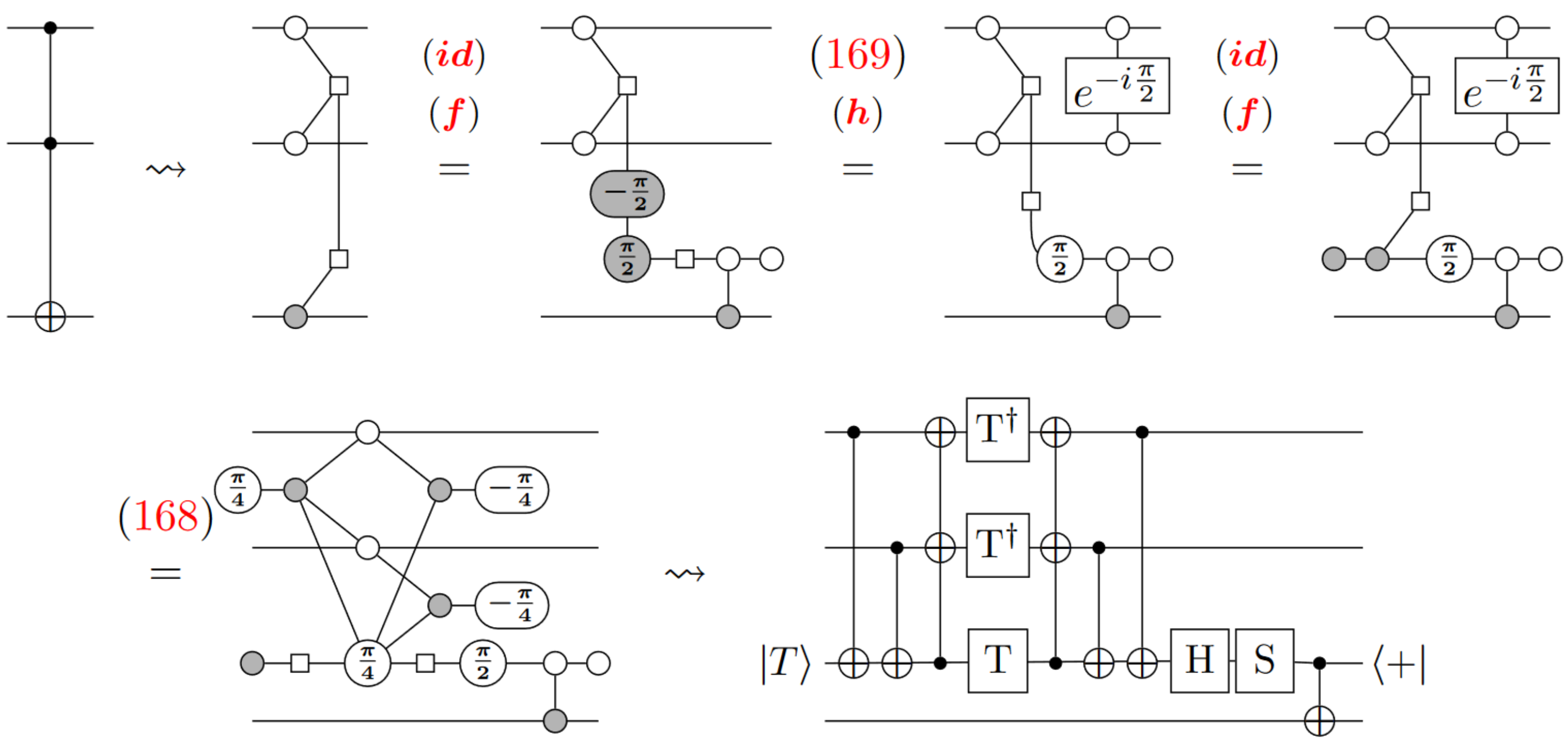
Miriam Backens, Aleks Kissinger



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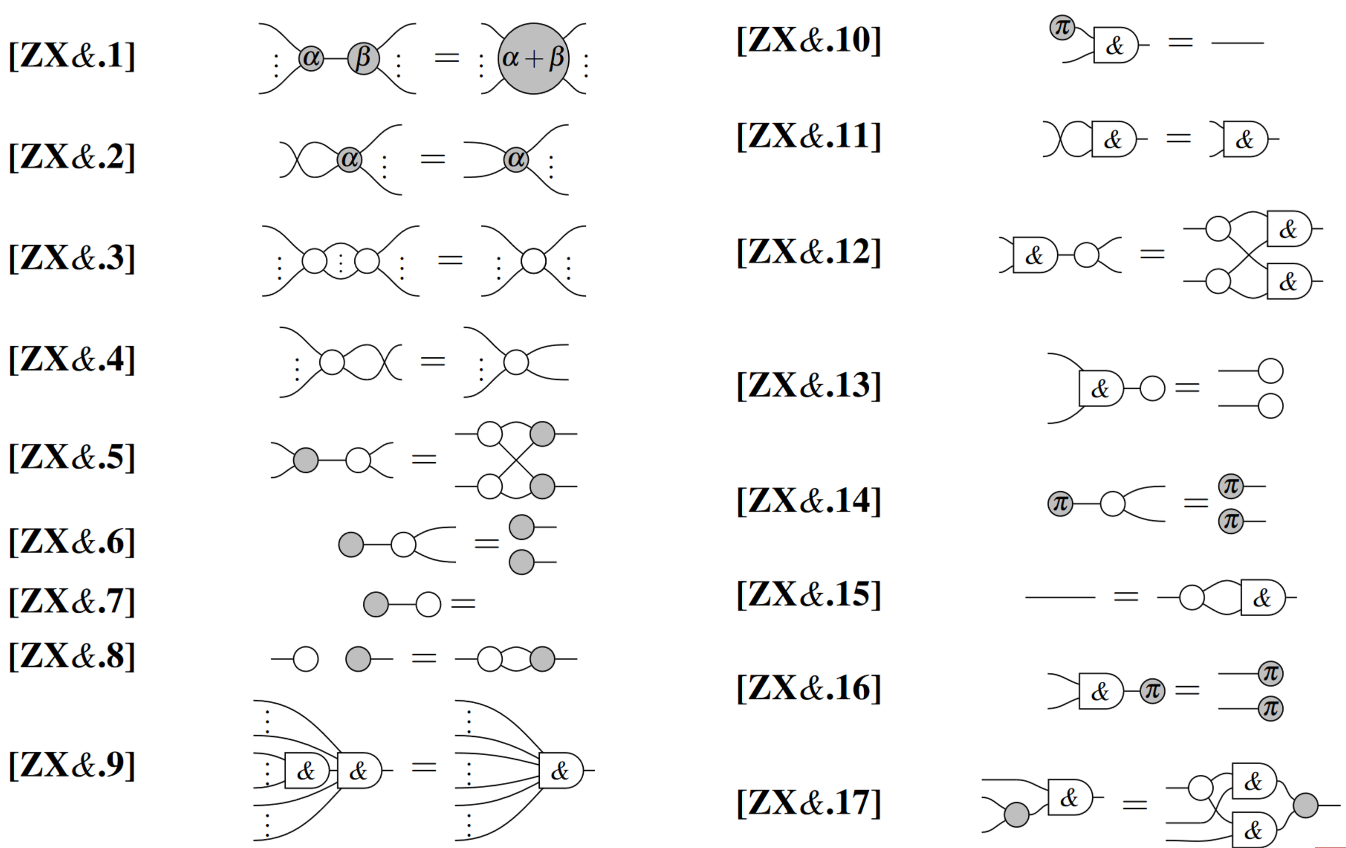

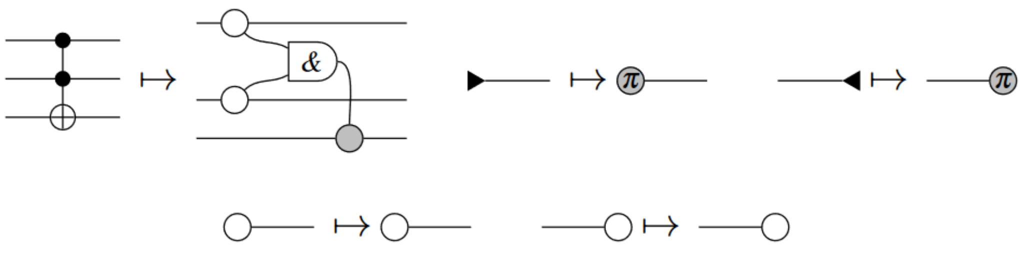

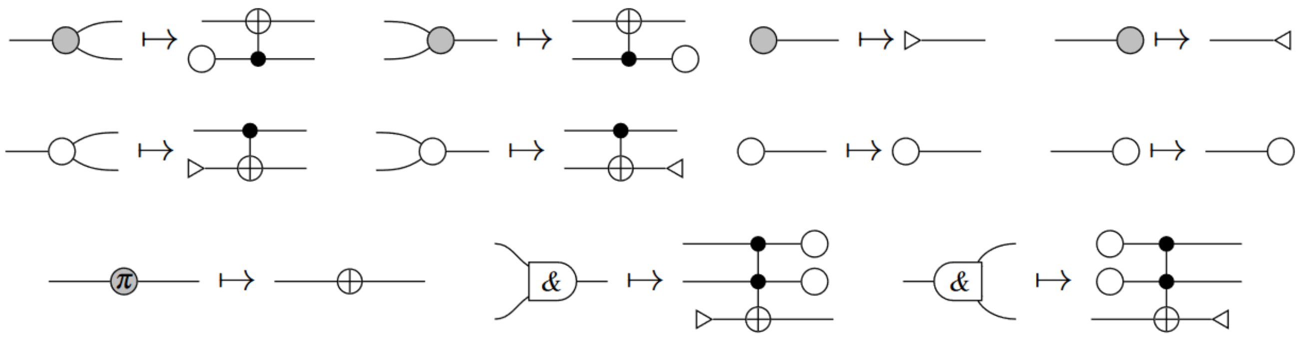

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The ZX&-calculus: A complete graphical calculus for classical circuits using spiders

Cole Comfort (University of Oxford)

Thank you!