Bosonic Quantum Interface: Characterization, Engineering, and Application

Kero Lau

Department of Physics, Simon Fraser University
Affiliate Fellow, Quantum Algorithm Institute

NSERC CRSNG

CANADA RESEARCH CHAIRS
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HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)
Fong, Poon, **HKL**, *arXiv:2212.05134*

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nault, John Gunnels

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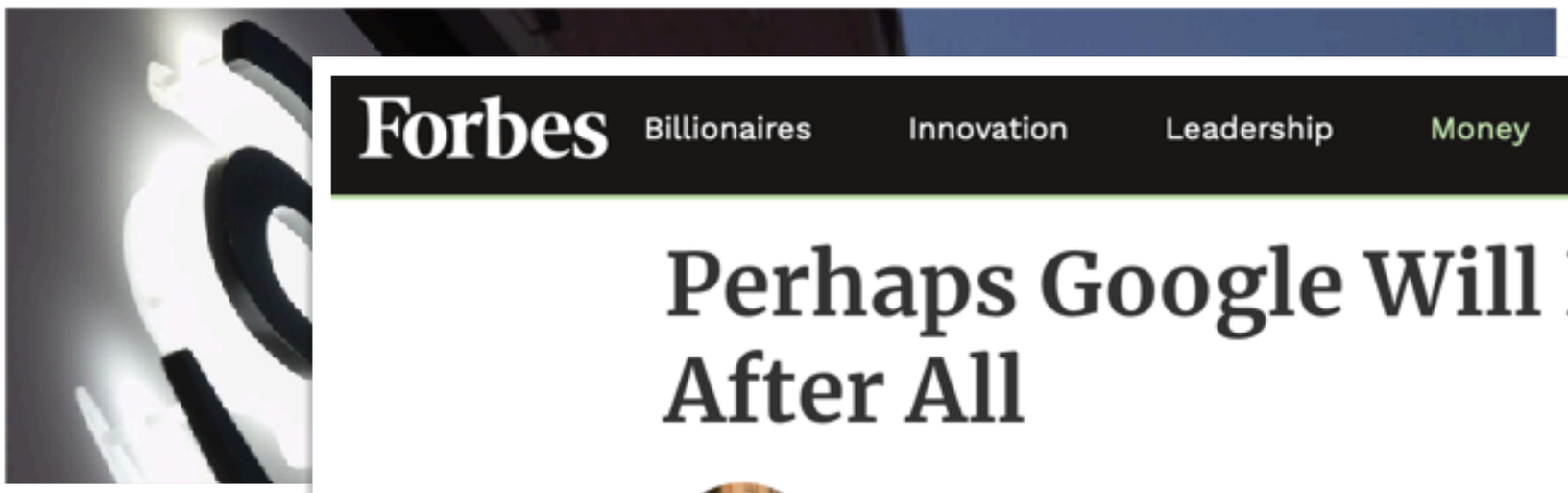
CIO JOURNAL

Amazon Rolls Out Quantum-Computing Service

Select customers will be able to test quantum algorithms, hardware



Forbes Billionaires Innovation Leadership Money Business Small Business Life

Perhaps Google Will Kill Bitcoin, After All

Billy Bambrough Contributor ⓘ

Crypto & Blockchain

I write about how bitcoin, crypto and blockchain can change the world.

Which quantum platform is the best?

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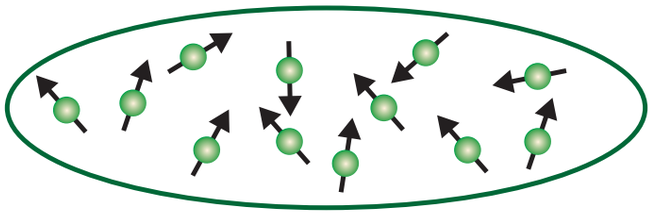
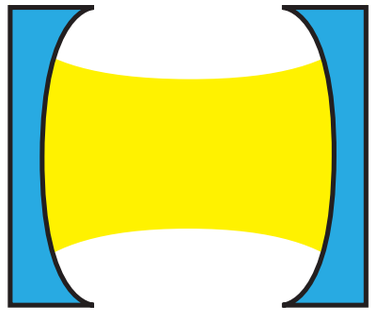
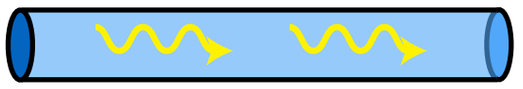
Solid-state spin



Microwave in cavity



Optical photon



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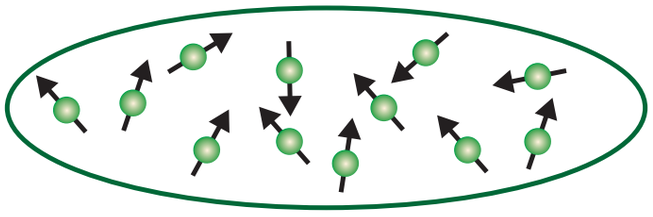

✅ Long memory time

❌ Hard to connect

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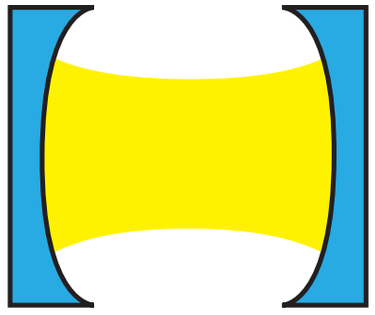

✅ High controllability

❌ Short memory time

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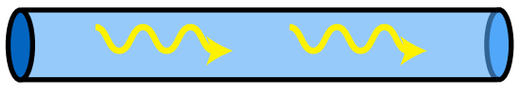
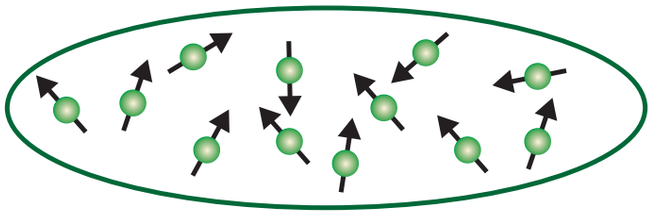


✅ Fast transmission

❌ Hard to store

~~Which quantum platform is the best?~~

Solid-state spin



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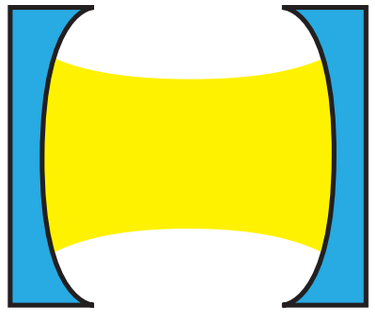

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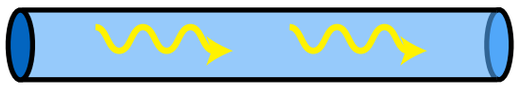

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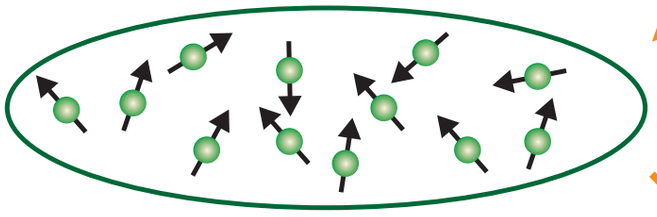

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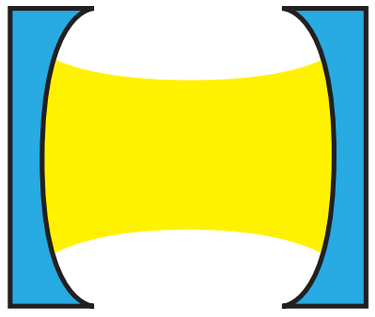

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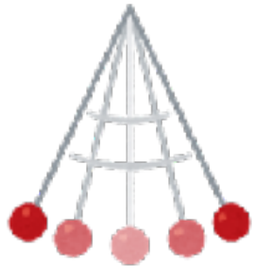
Build interface to connect different platforms

Bosonic system = Harmonic oscillators

$$H = \frac{1}{2}Q^2 + \frac{1}{2}P^2$$



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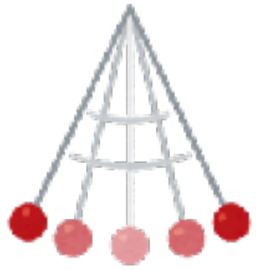
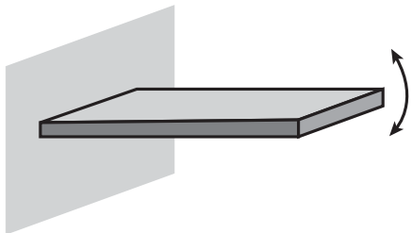
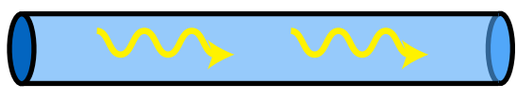
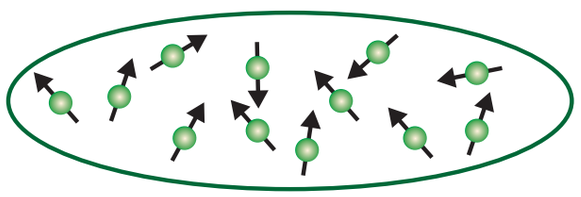


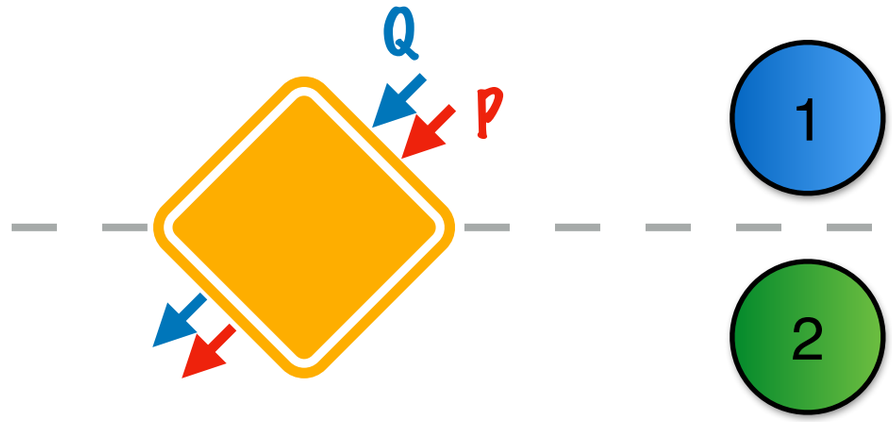
	Q quadrature	P quadrature
 Mechanical oscillator	Position	Momentum
 Photon/Microwave	Vector potential	Electric field
 Spin ensemble	# of spins pointing X	# of spins pointing Y

Example: State transfer

Perfect swap

$$Q_2(T) = Q_1(0)$$

$$P_2(T) = P_1(0)$$



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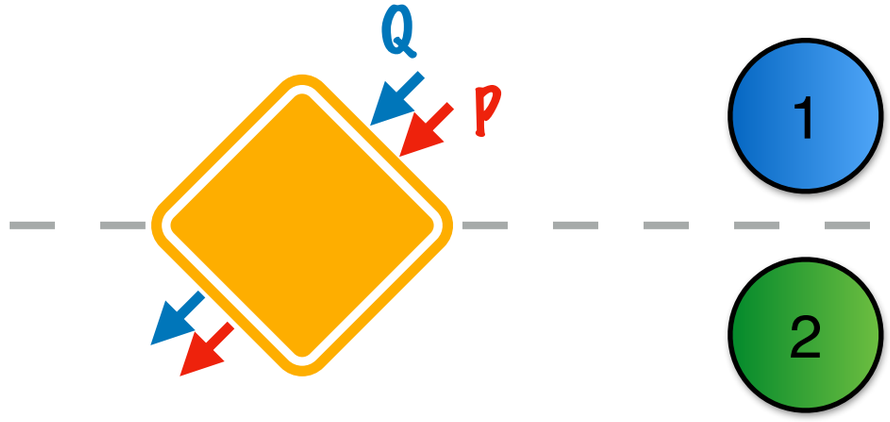
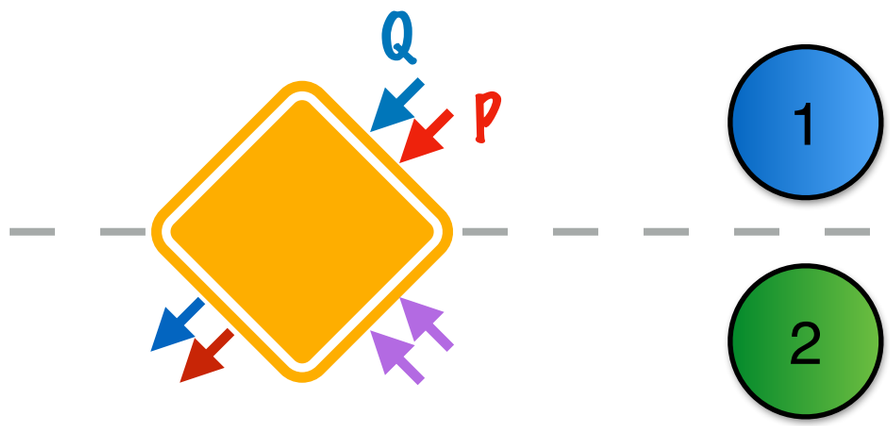


Imperfect swap

$$Q_2(T) = T_{QQ}Q_1(0) + T_{QP}P_1(0) + R_{QQ}Q_2(0) + R_{QP}P_2(0)$$

$$P_2(T) = T_{PQ}Q_1(0) + T_{PP}P_1(0) + R_{PQ}Q_2(0) + R_{PP}P_2(0)$$



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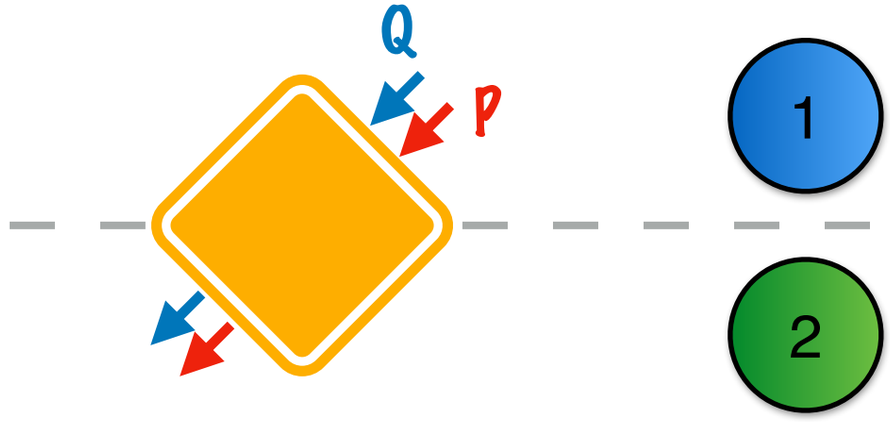

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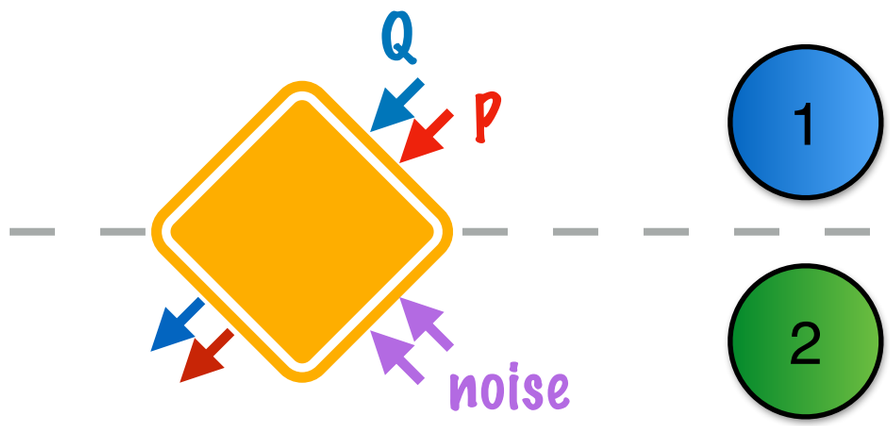

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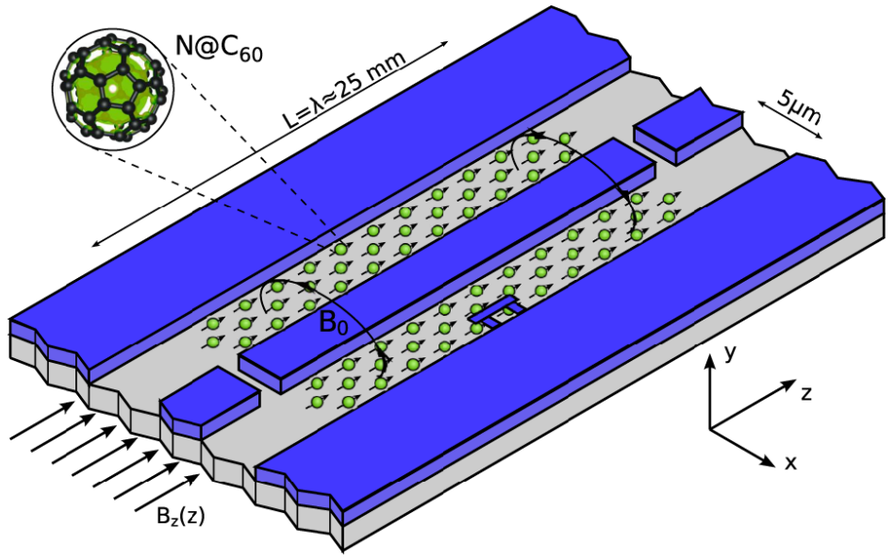
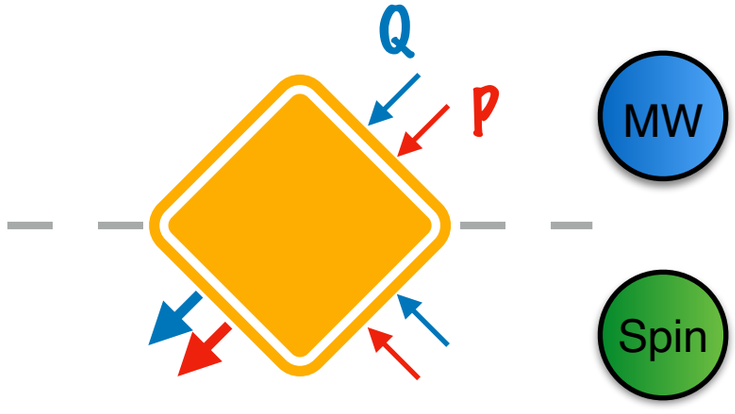


Microwave-spin interface

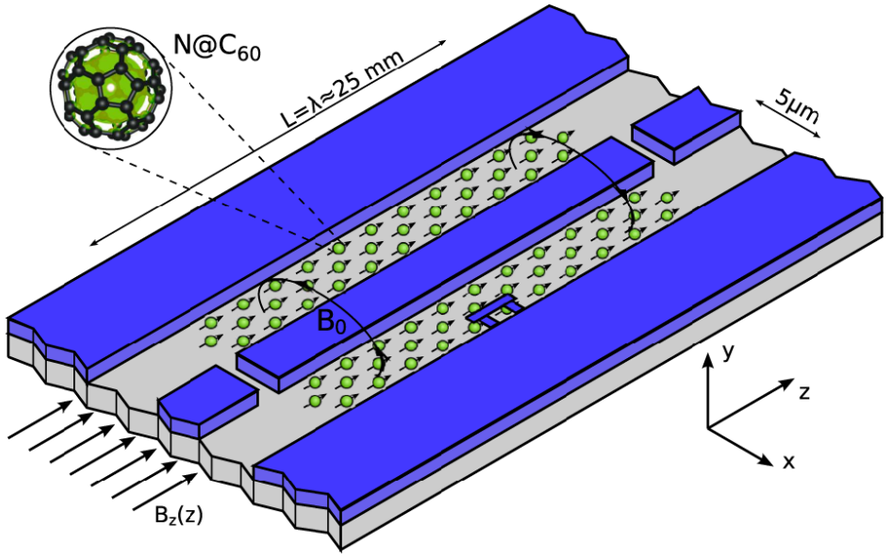
Wesenberg et al, PRL (2009)

Insufficient interaction strength



Incomplete transmission

Imperfect state transfer



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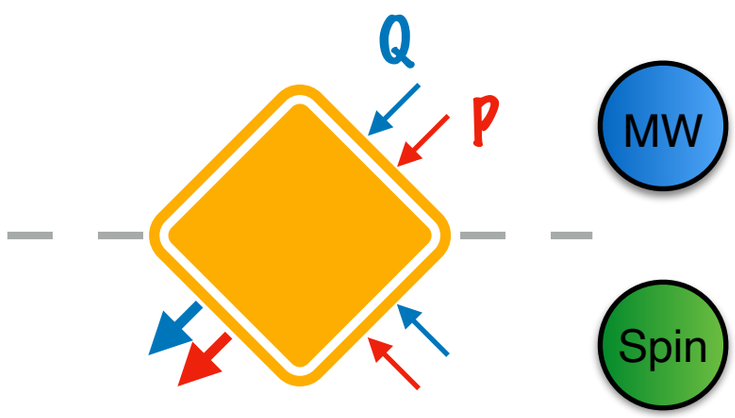

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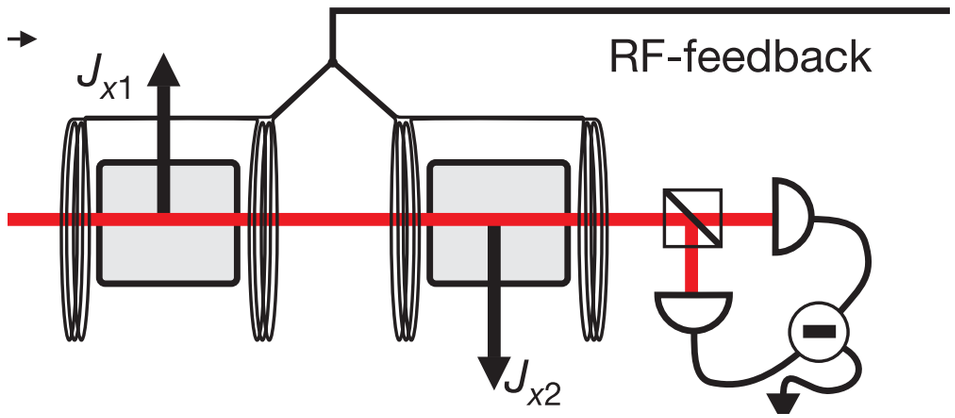
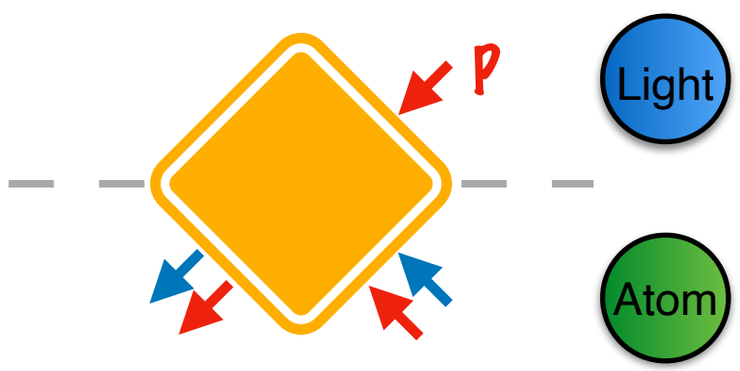


Light-atom interface

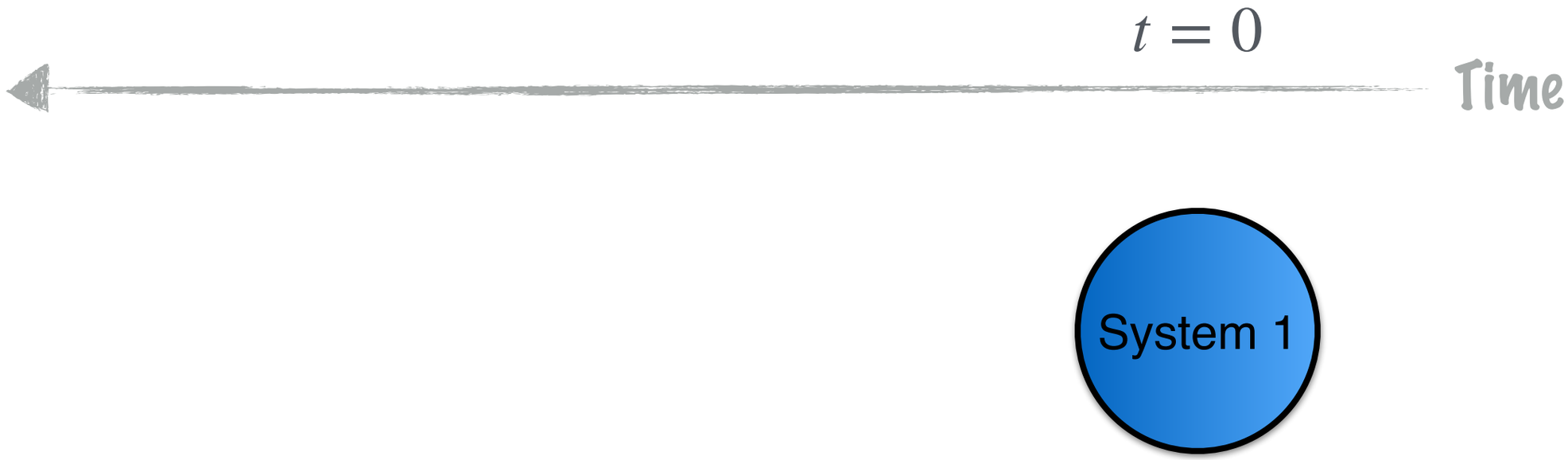
Julsgaard et al, Nature (2004)

Undesired type of interaction



Partial transmission

Can we "repair" the interface?



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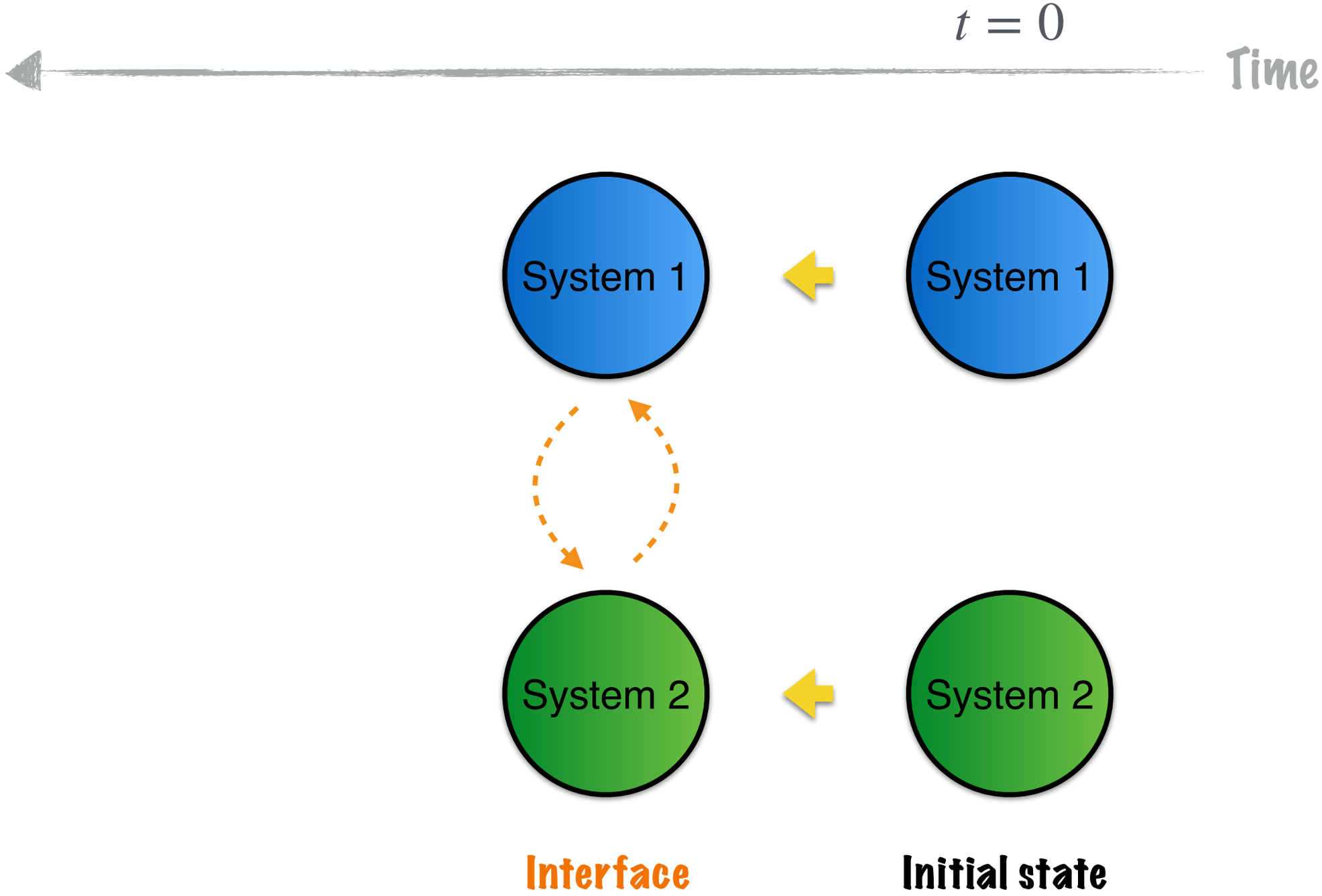

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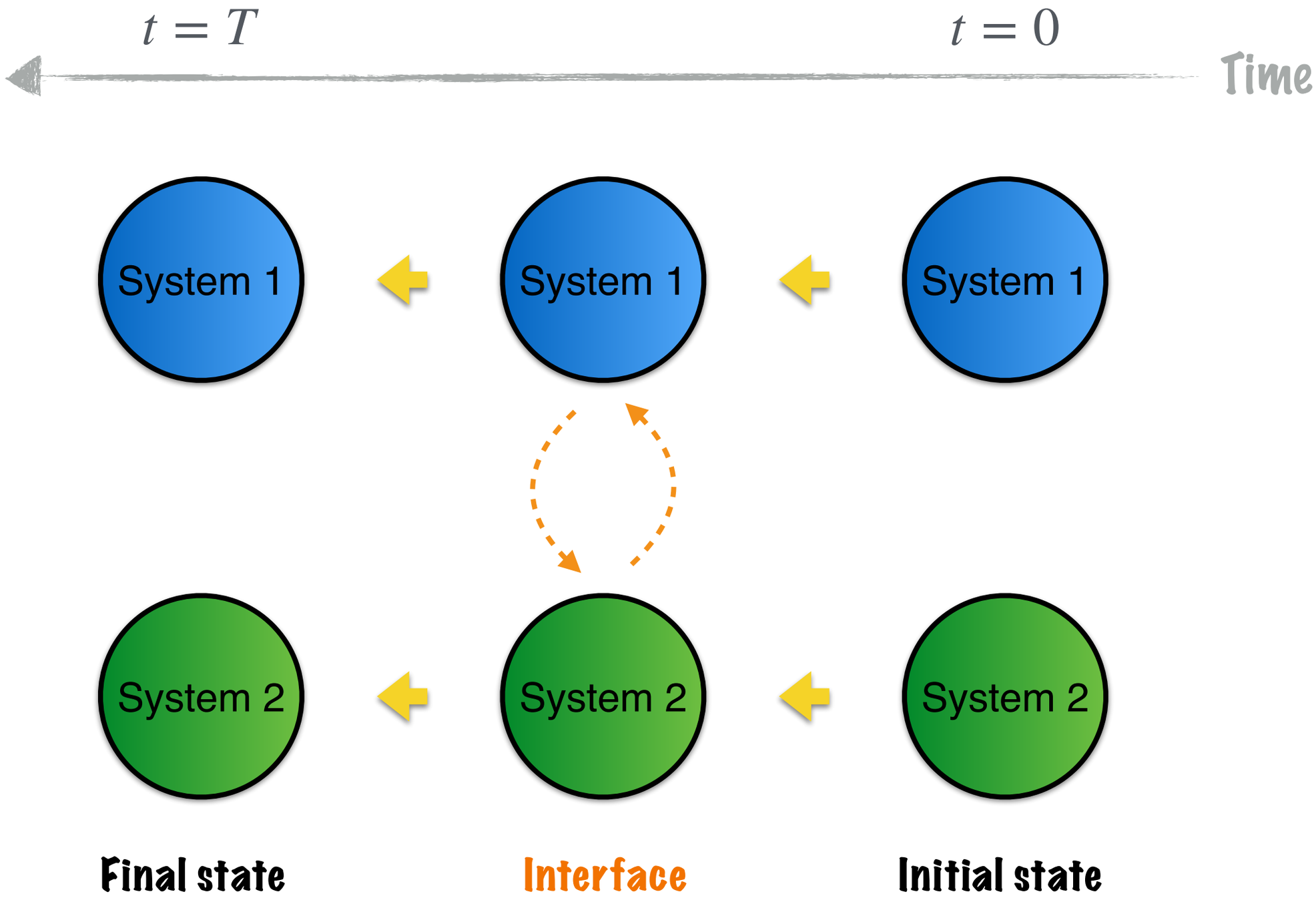

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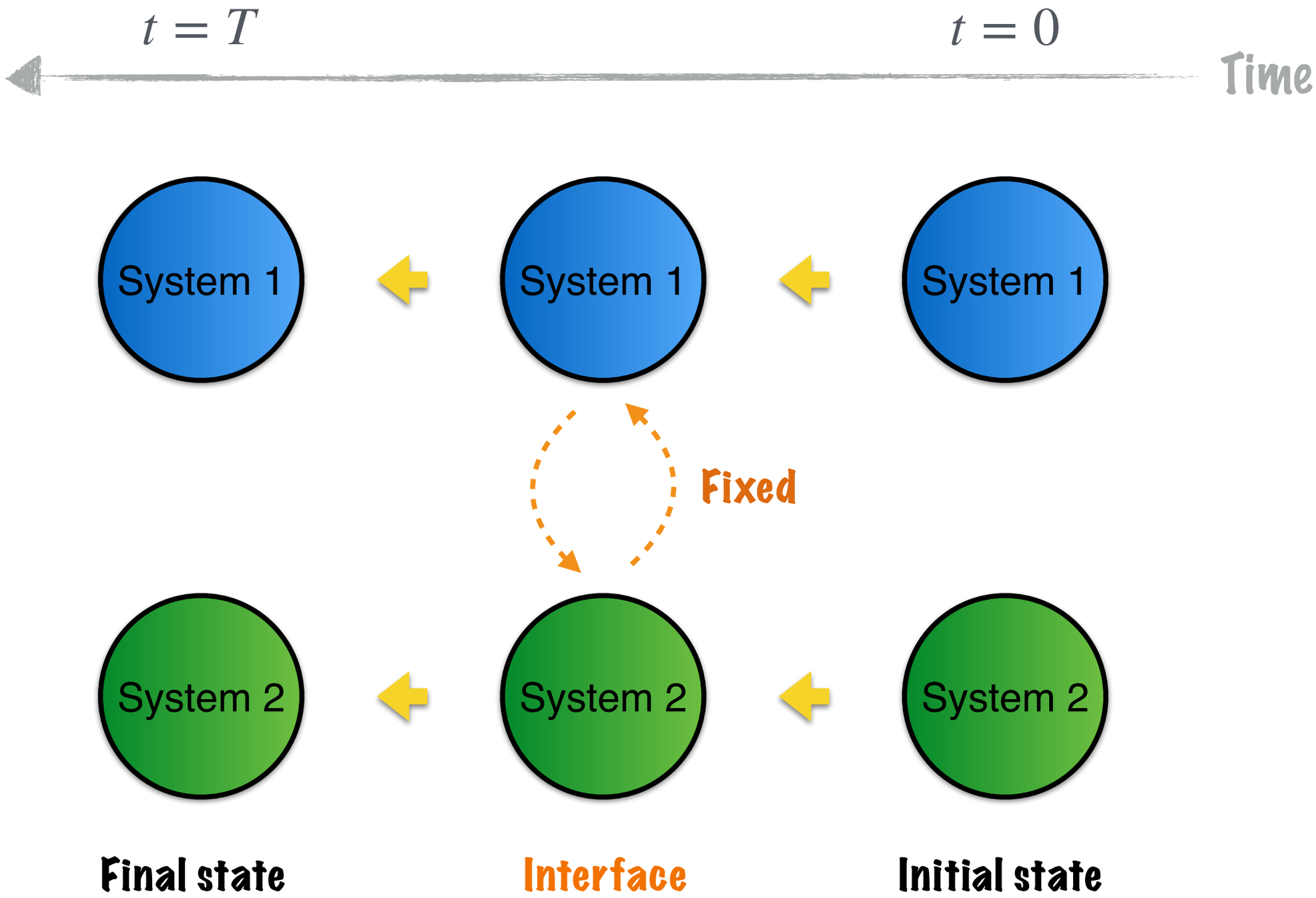

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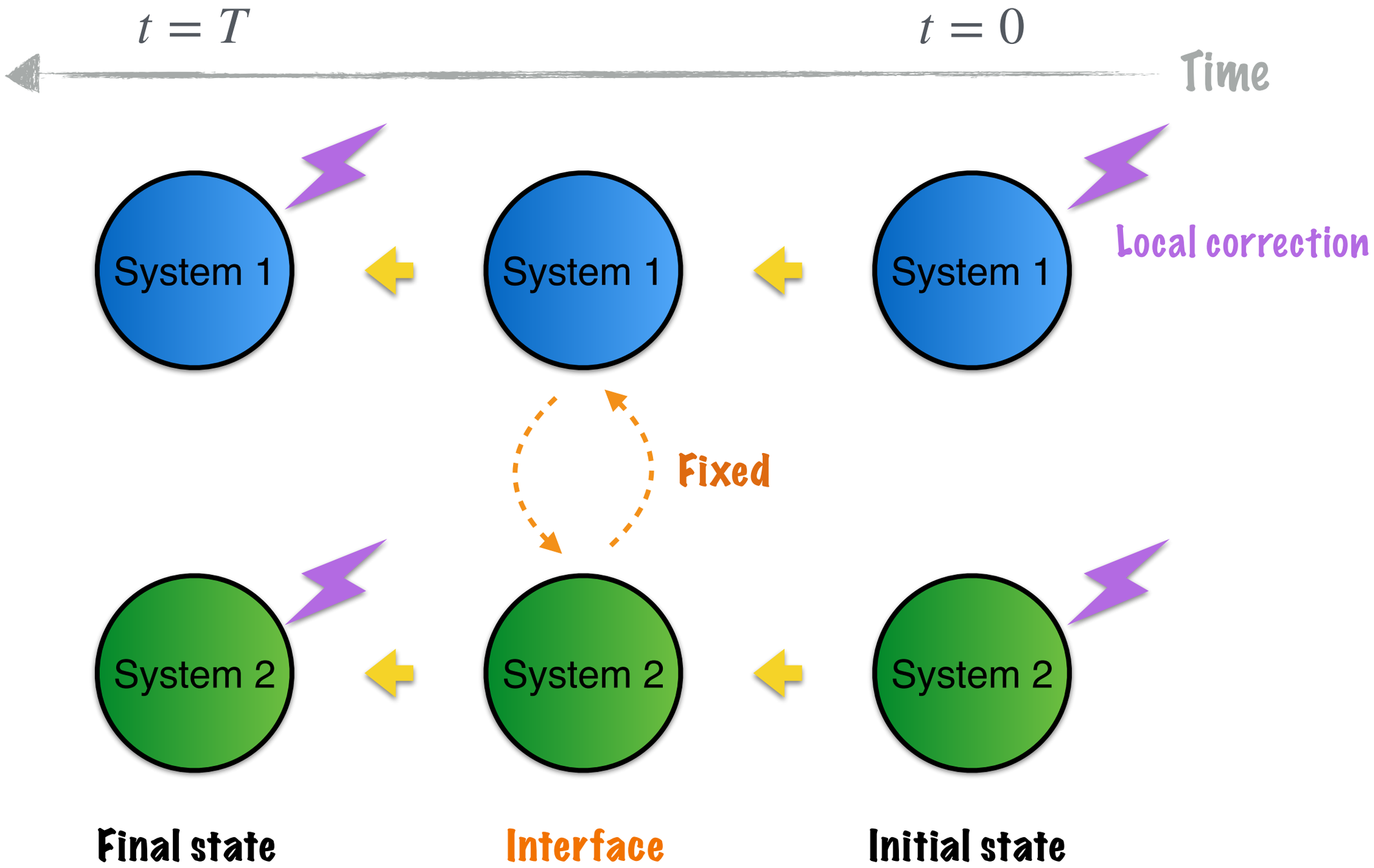

What can we do on a single oscillator?

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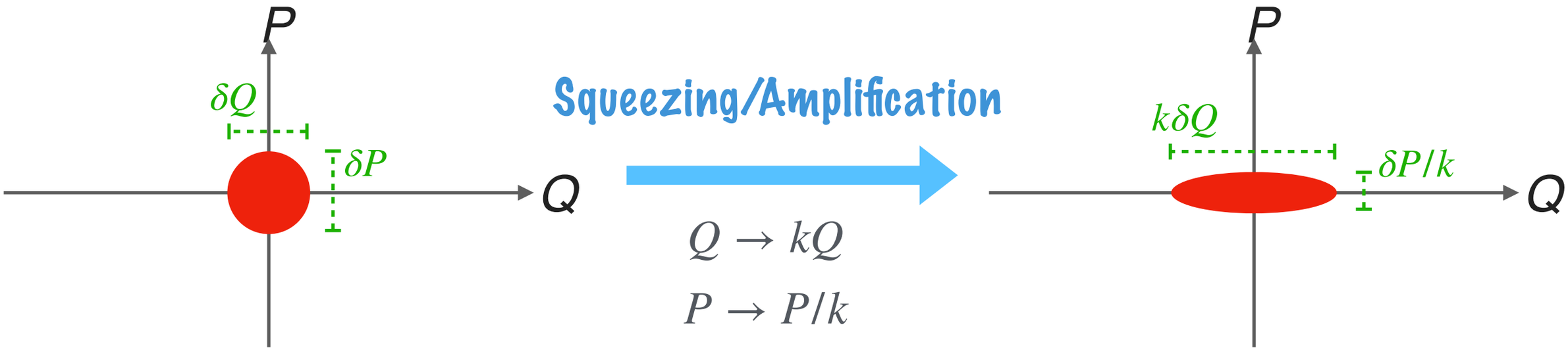

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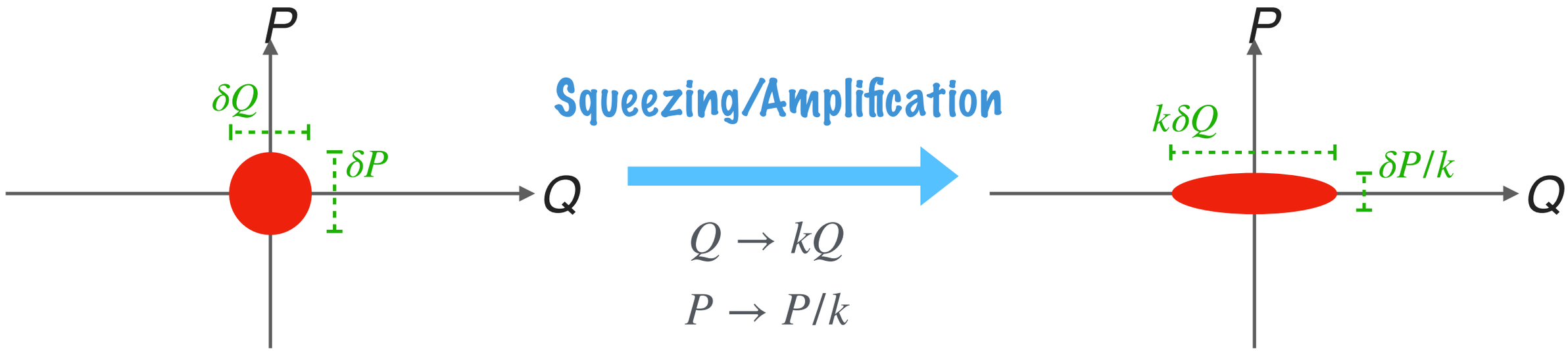

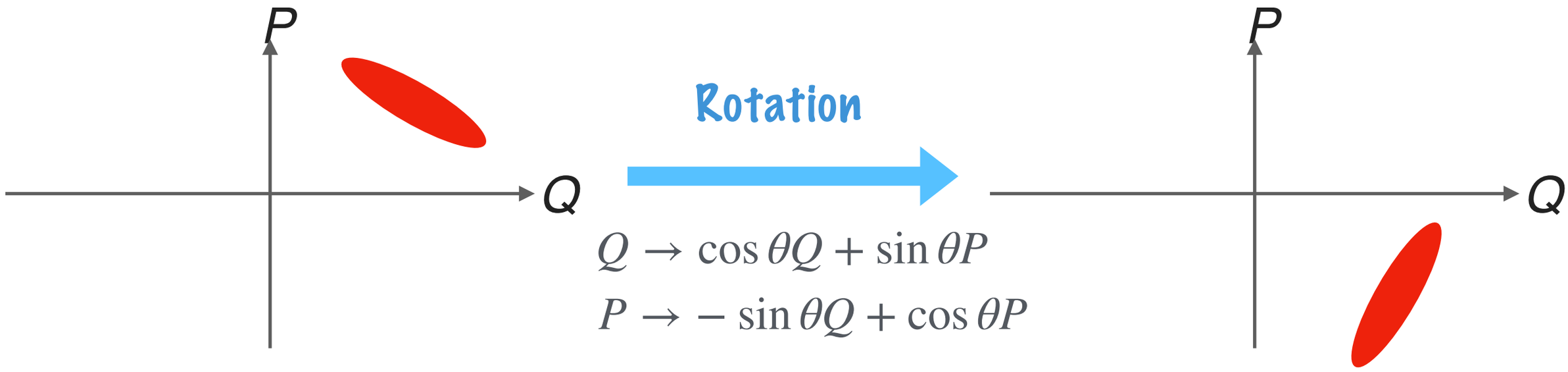

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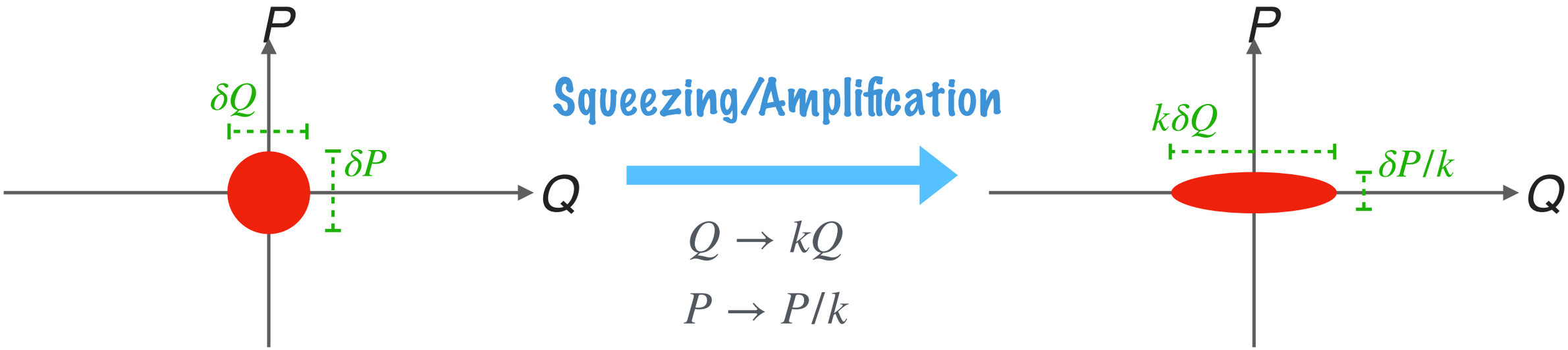

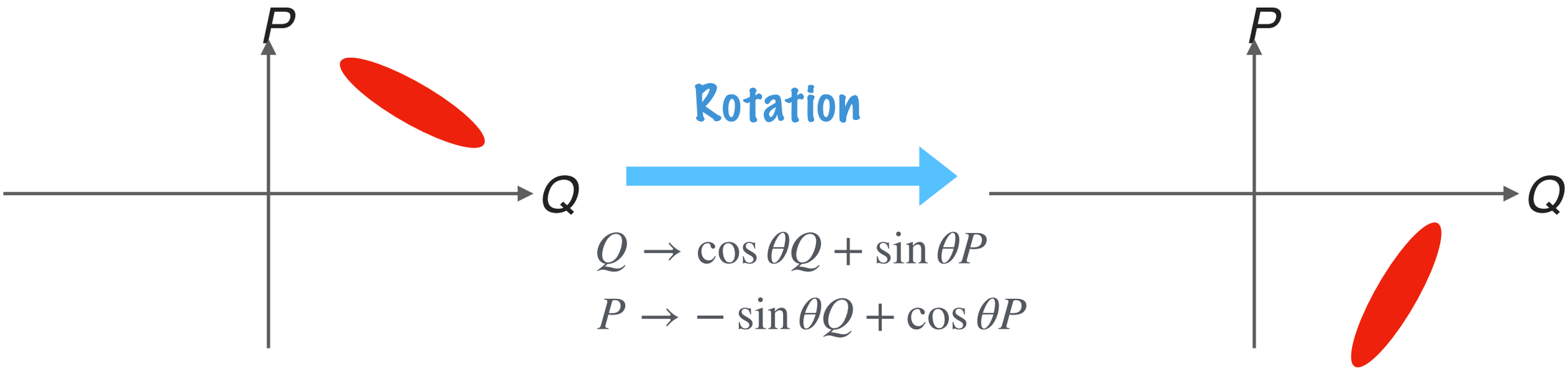

Are they useful for correcting an interface?

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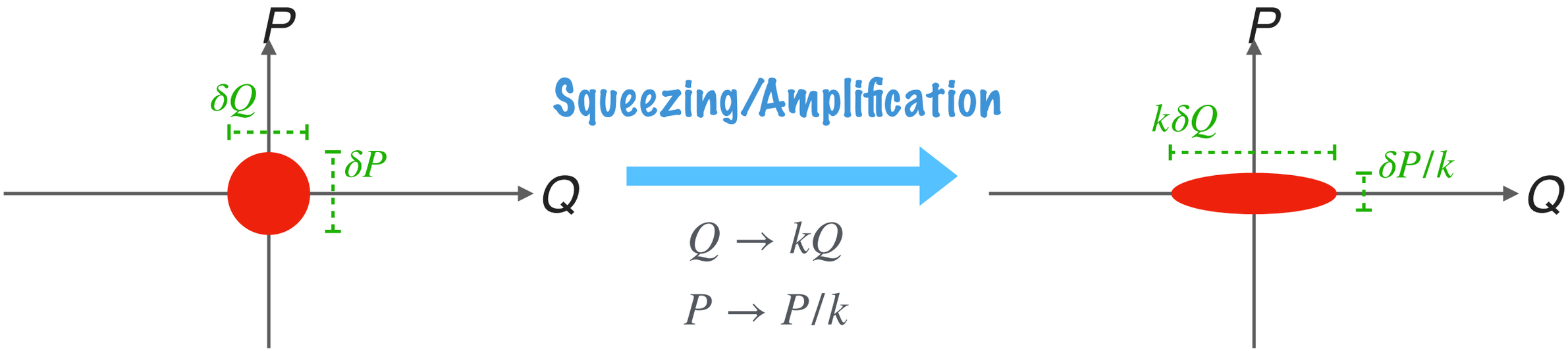

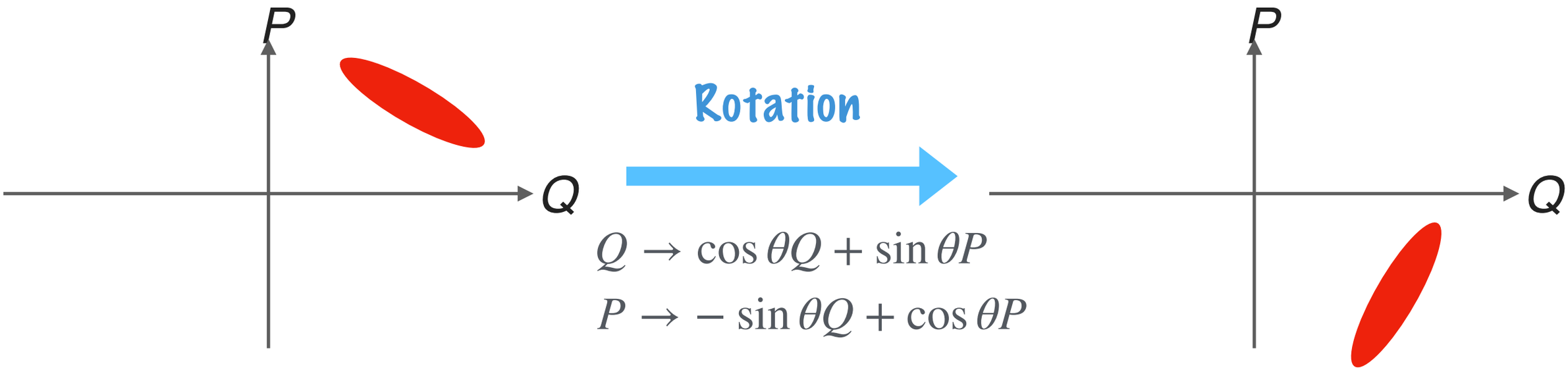

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If we can apply arbitrary single-mode correction, how can we convert an interface to another?

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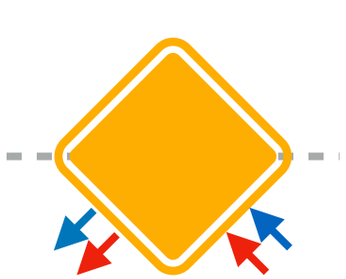
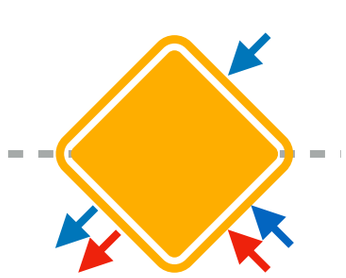
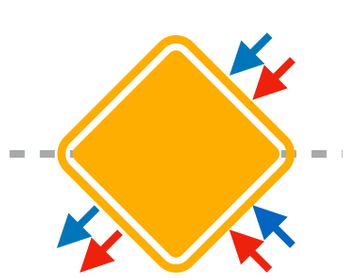
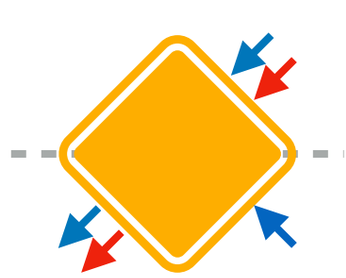
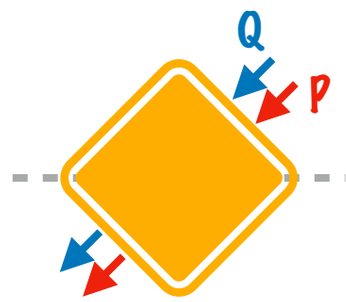
Inconvertible classes of interface

Local	QND gate	Beam splitter, Two-mode squeezing	SWAP+QND	SWAP
				

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	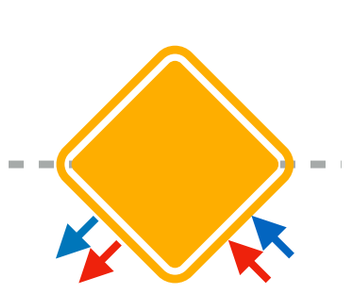	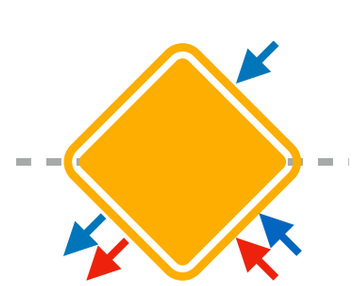	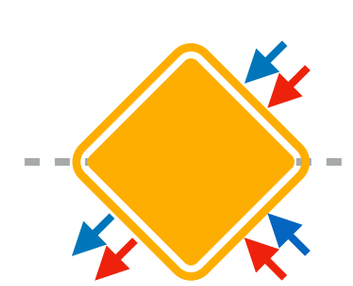	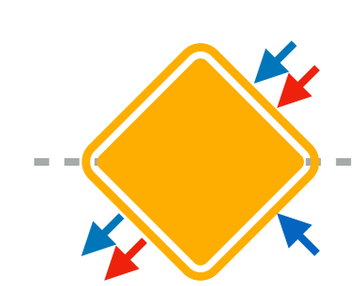	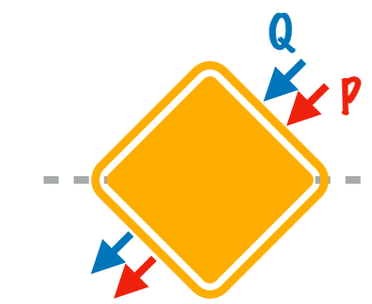
Transmitted quadratures	0	1	2	2	2
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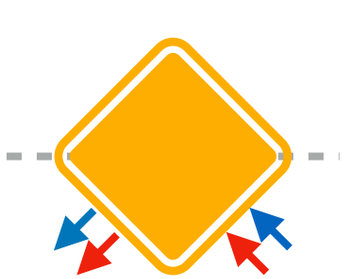
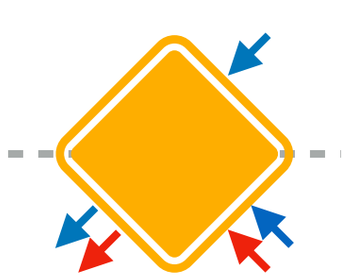
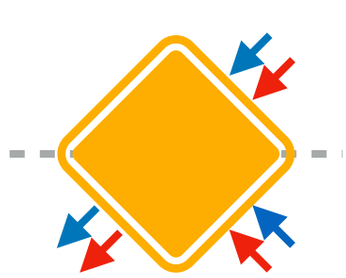
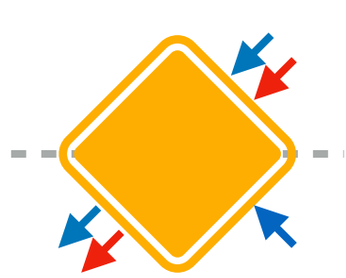
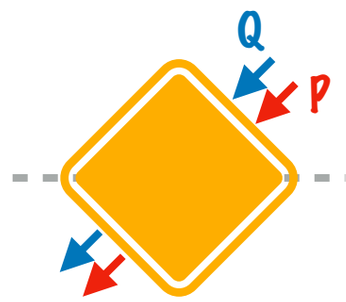
Inconvertible classes of interface

	Local	QND gate	Beam splitter, Two-mode squeezing	NEW SWAP+QND	SWAP
					
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	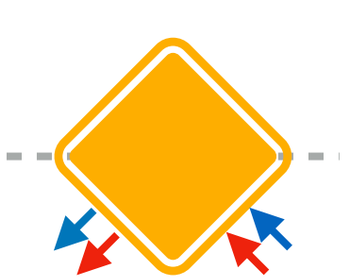	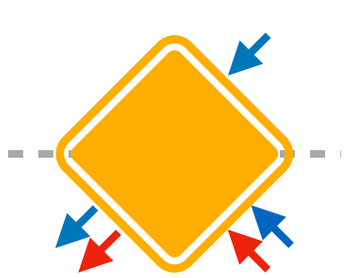	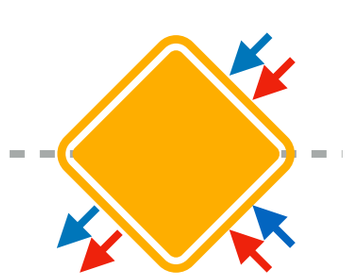	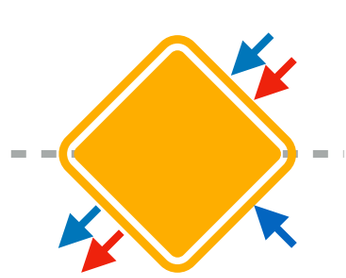	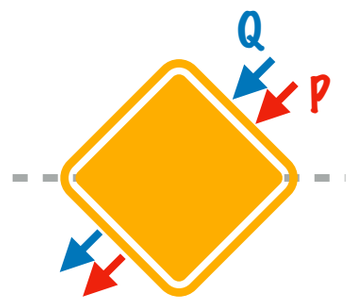
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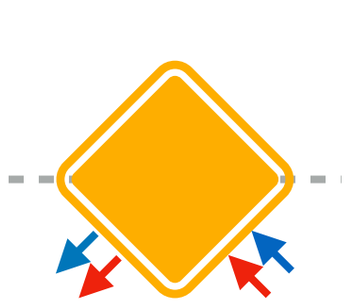
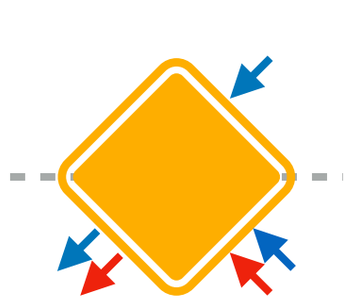
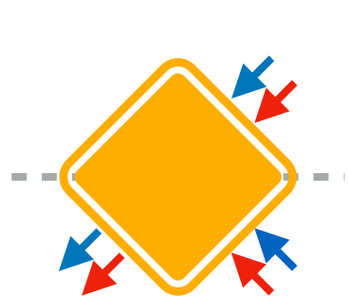
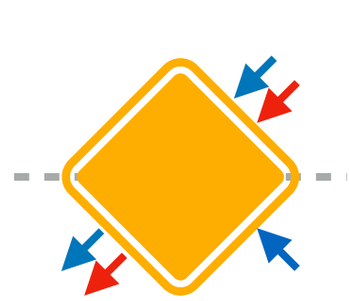
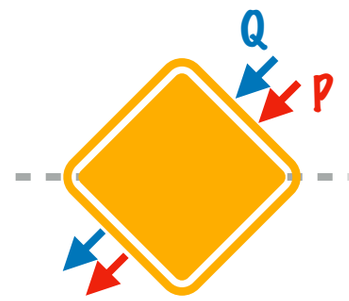
Inconvertible classes of interface

	Local	QND gate	Beam splitter, Two-mode squeezing	SWAP+QND (NEW)	SWAP
					
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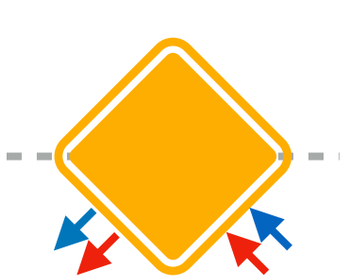
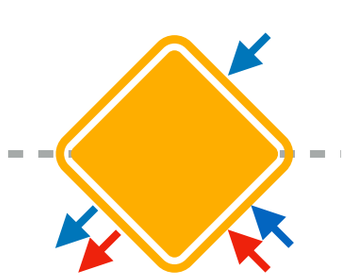
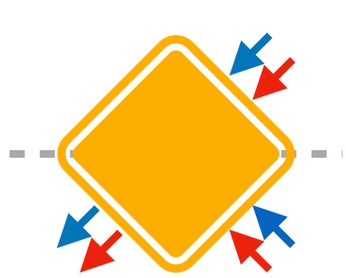
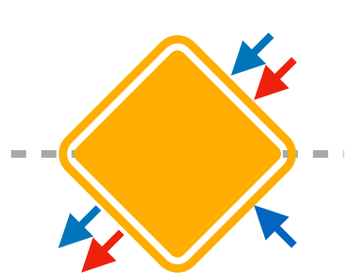
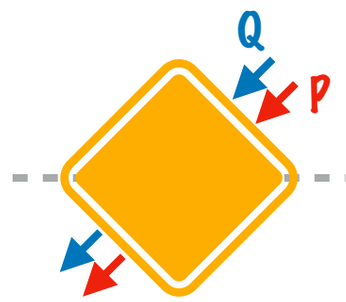
Transmission matrix — Reflection matrix

If we can apply arbitrary single-mode correction, how can we convert an interface to another?

Inconvertible classes of interface

NEW

	Local	QND gate	Beam splitter, Two-mode squeezing	SWAP+QND	SWAP
					
Transmitted quadratures	0	1	2	2	2
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Rank

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Transmission matrix

Reflection matrix

How can we fix imperfect interface?

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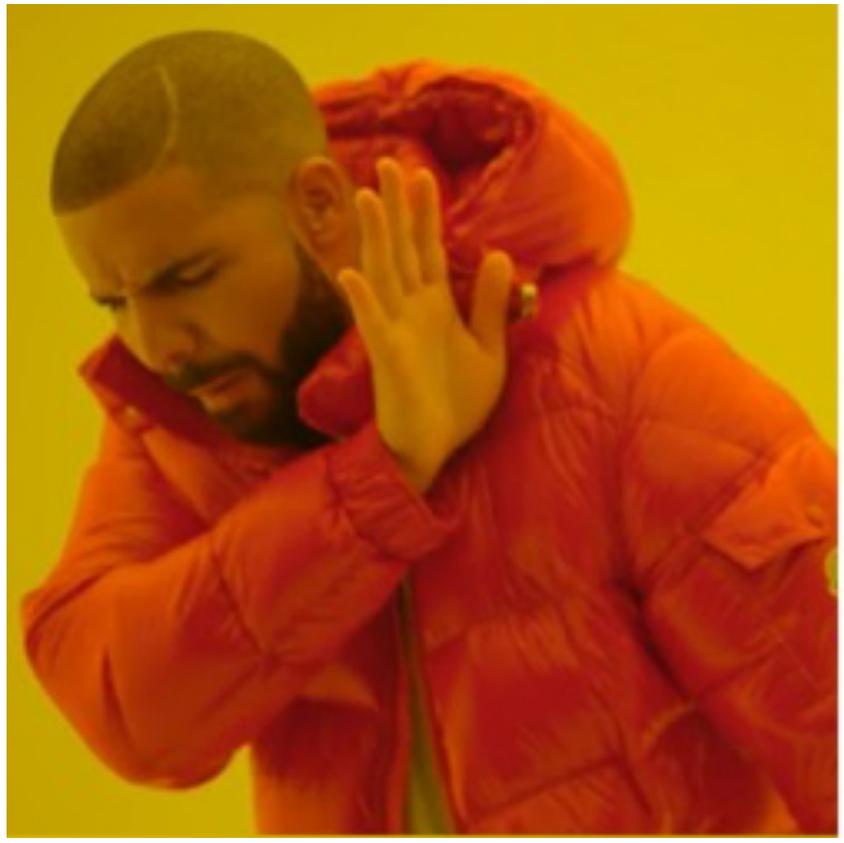


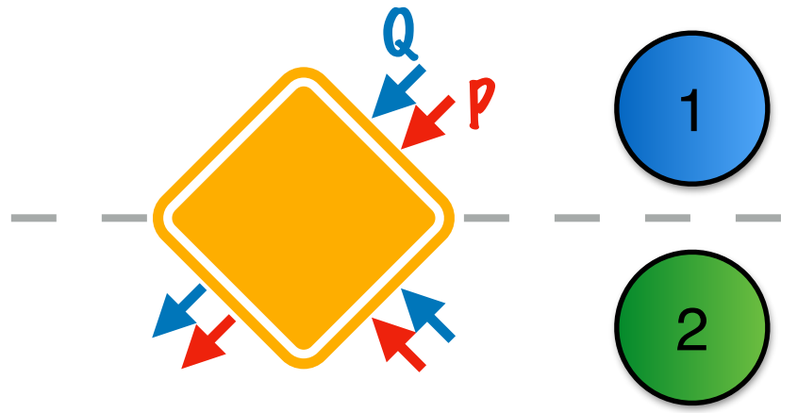
Just ask experimentalists to improve their system

How can we fix imperfect interface?

Just ask experimentalists to improve their system

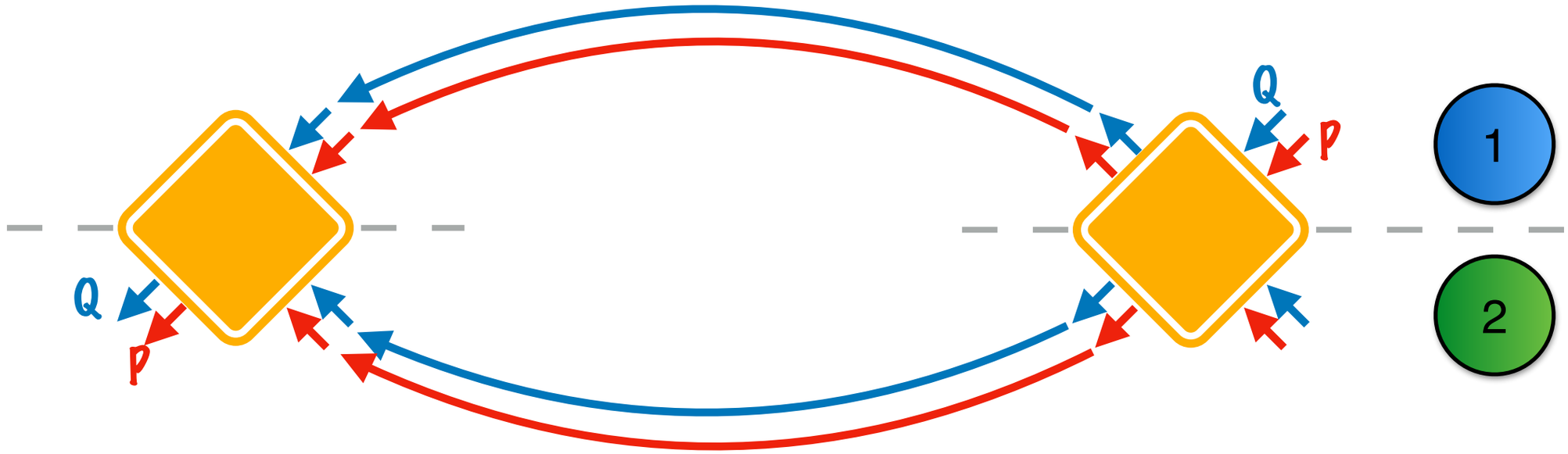
Tell experimentalists clever tricks to control their system

If one interface is bad...



If one interface is bad...

...then use it again!



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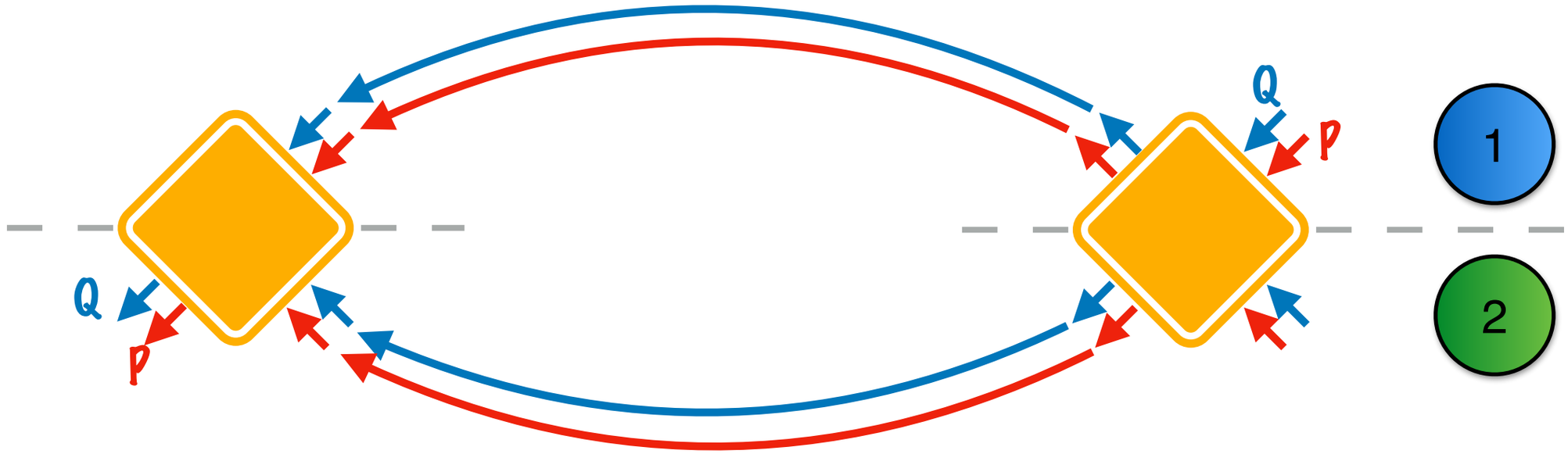
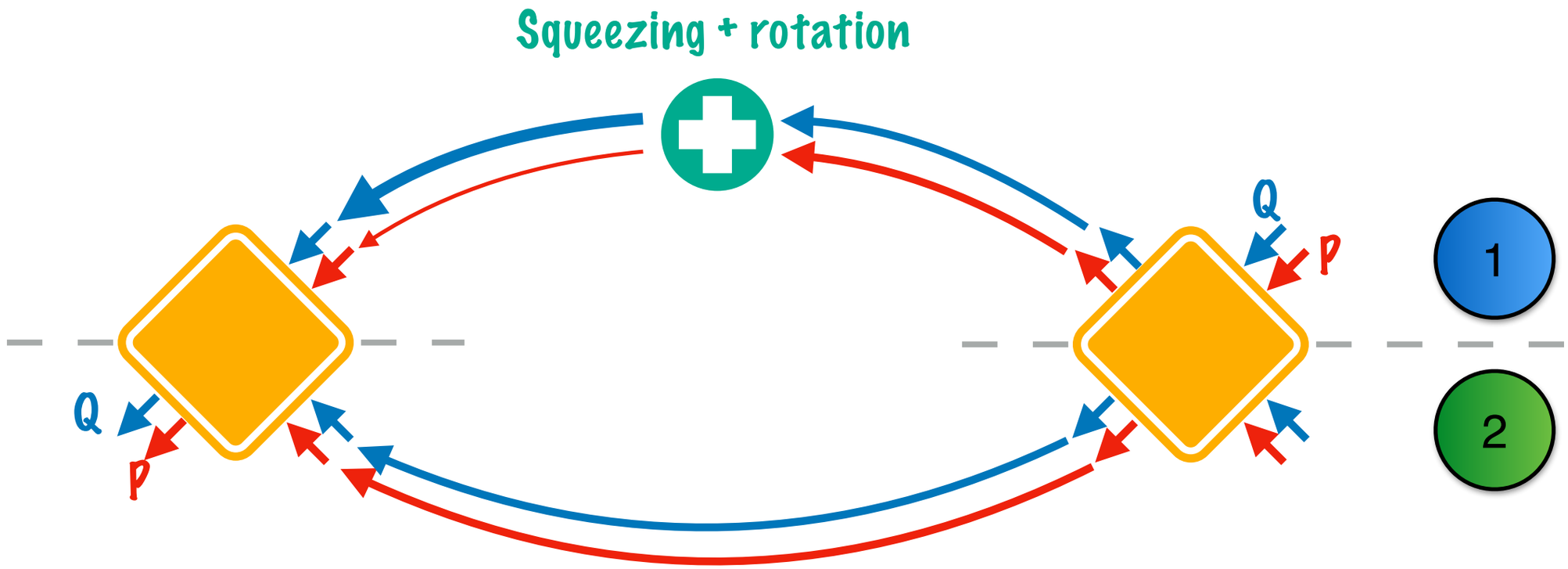


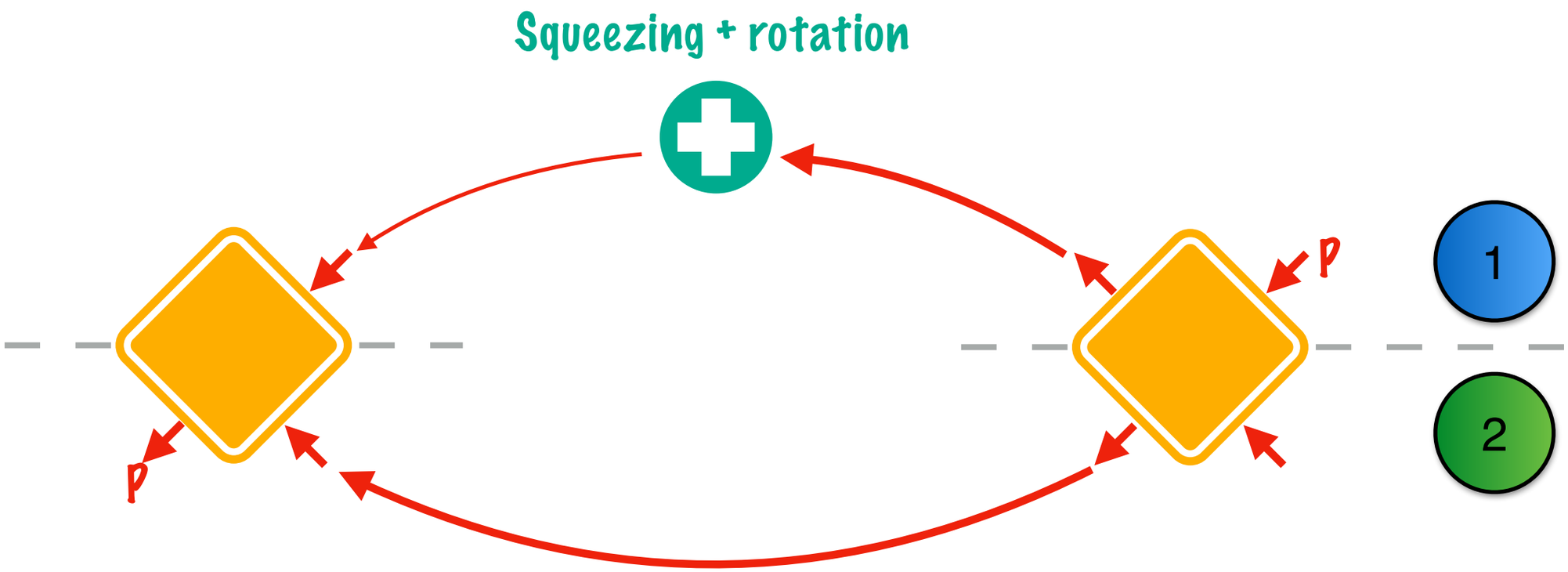
Two wrongs make a right, too good to be true?

Trick: apply single-mode correction in between



HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

Trick: apply single-mode correction in between



HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

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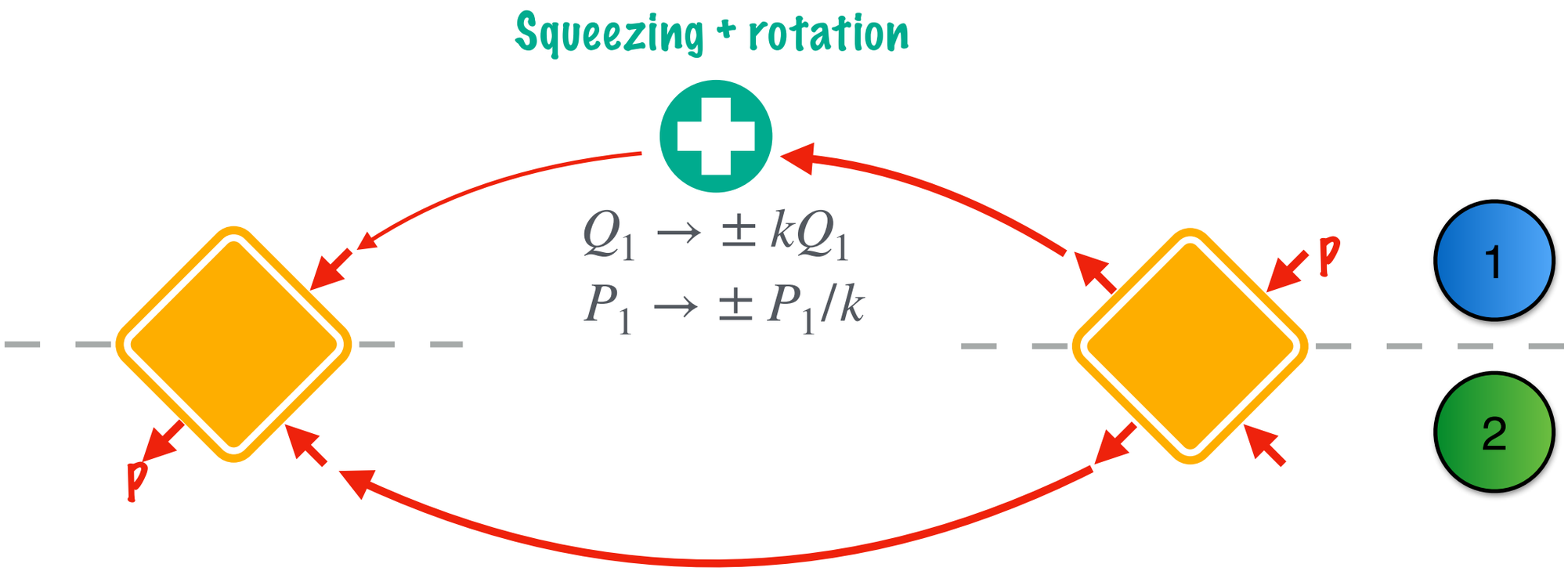

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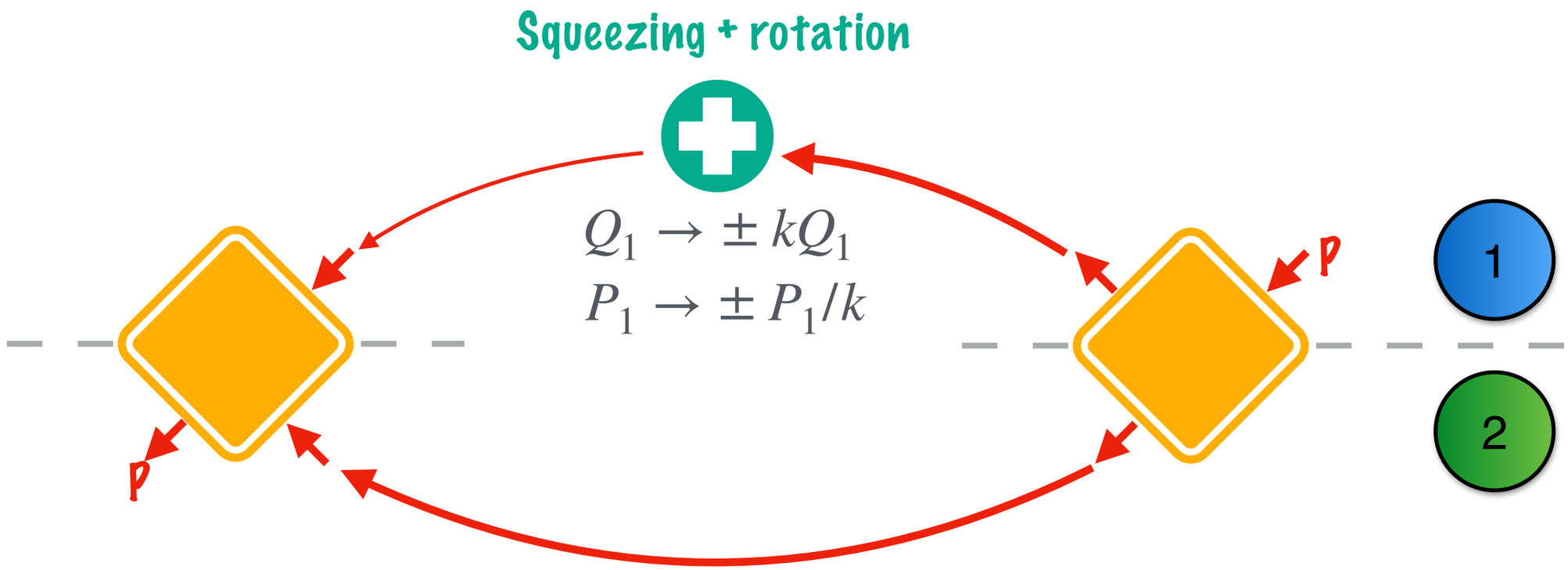

Destructive interference

HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

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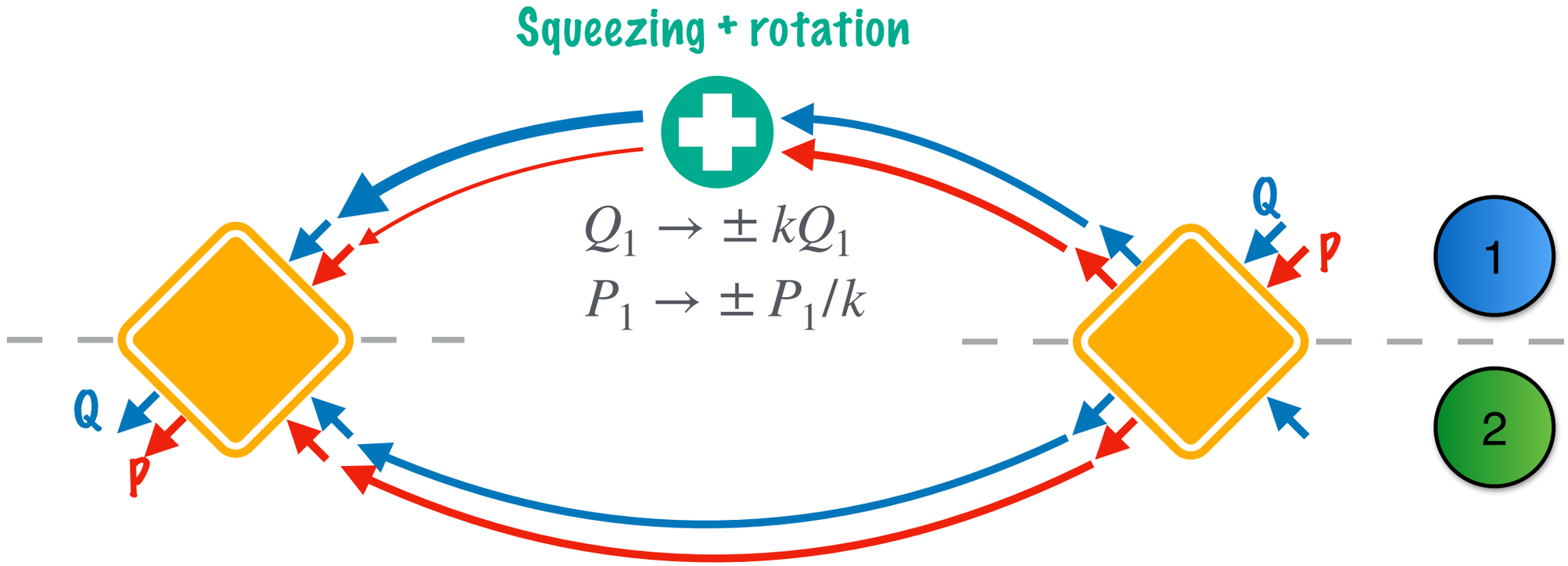

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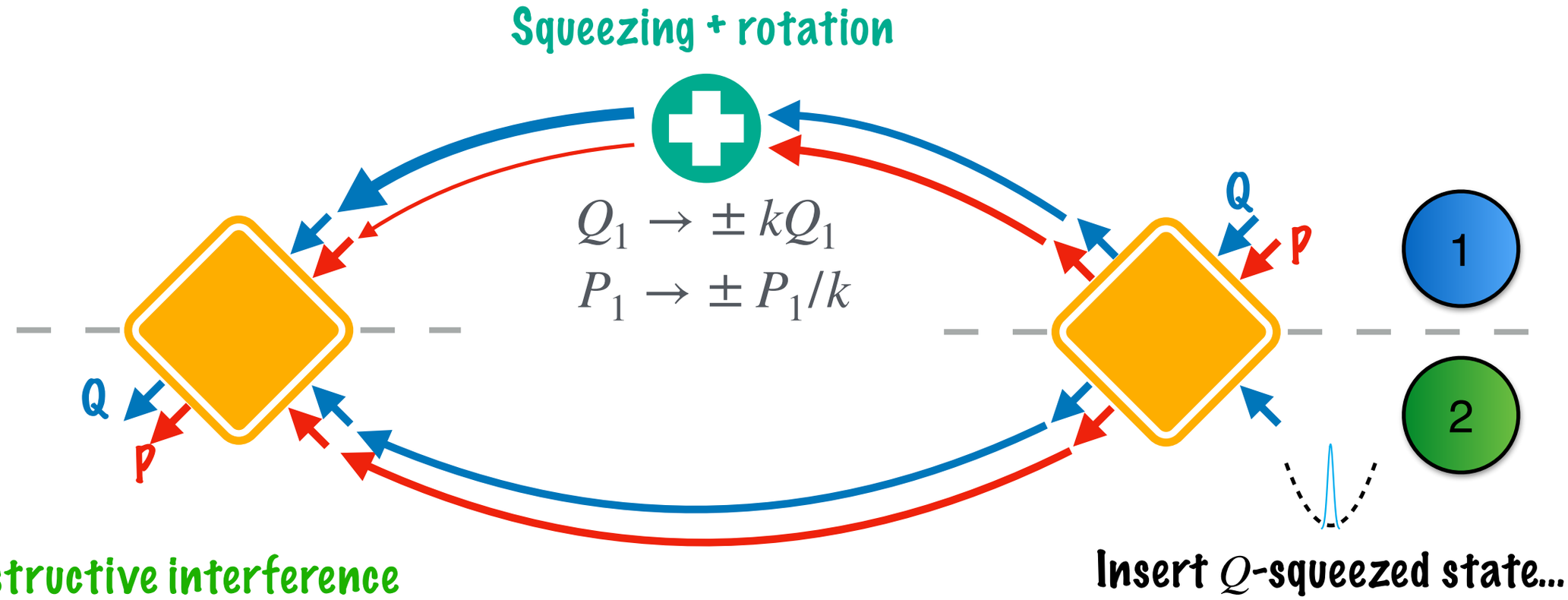

HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

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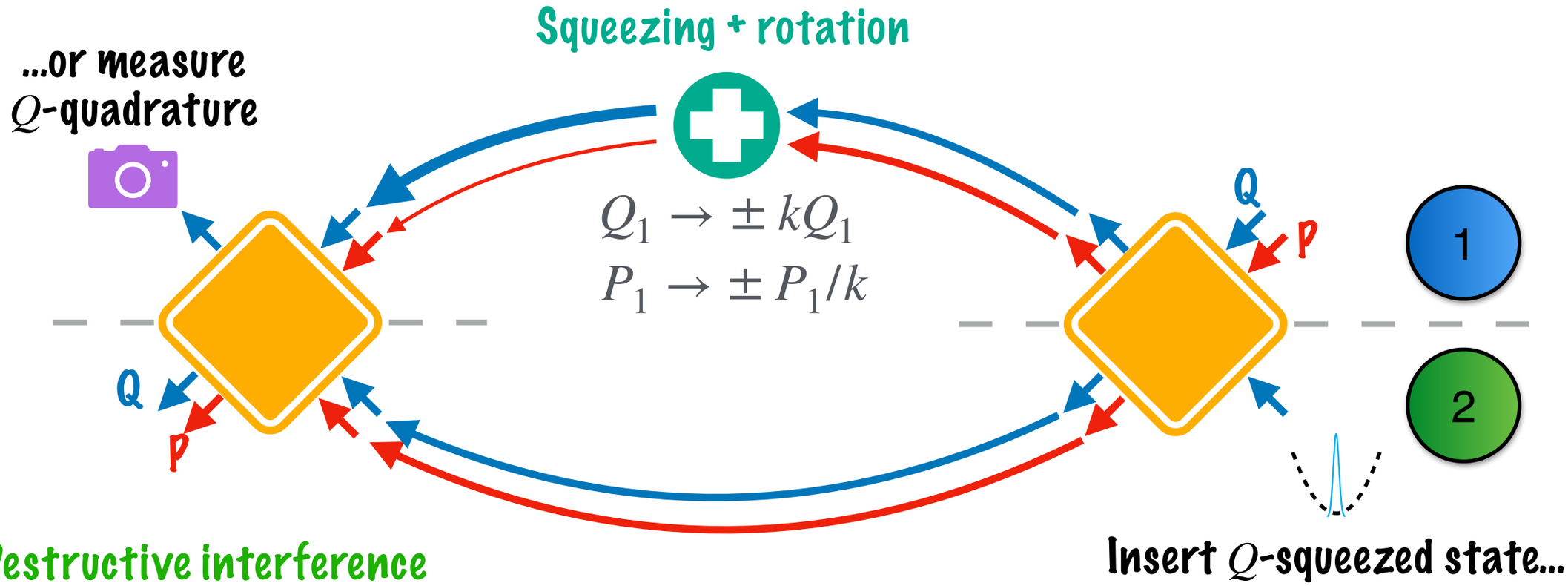

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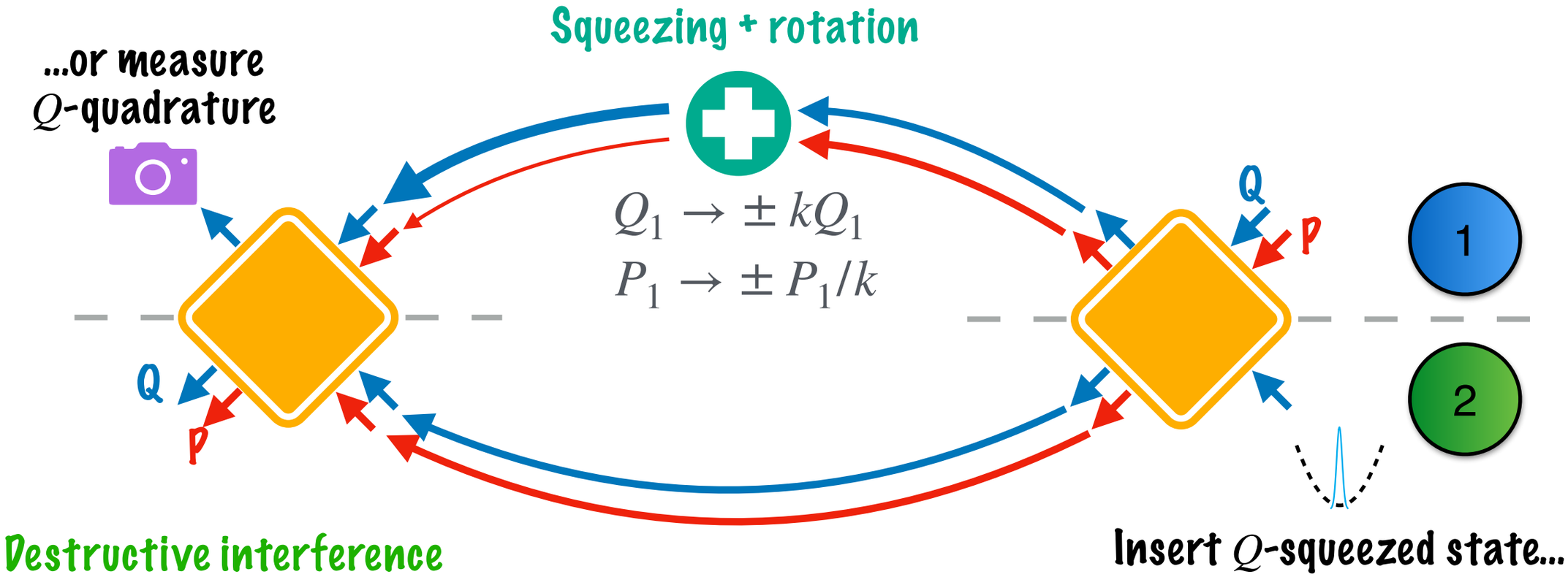

Overall state transfer becomes perfect!

HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

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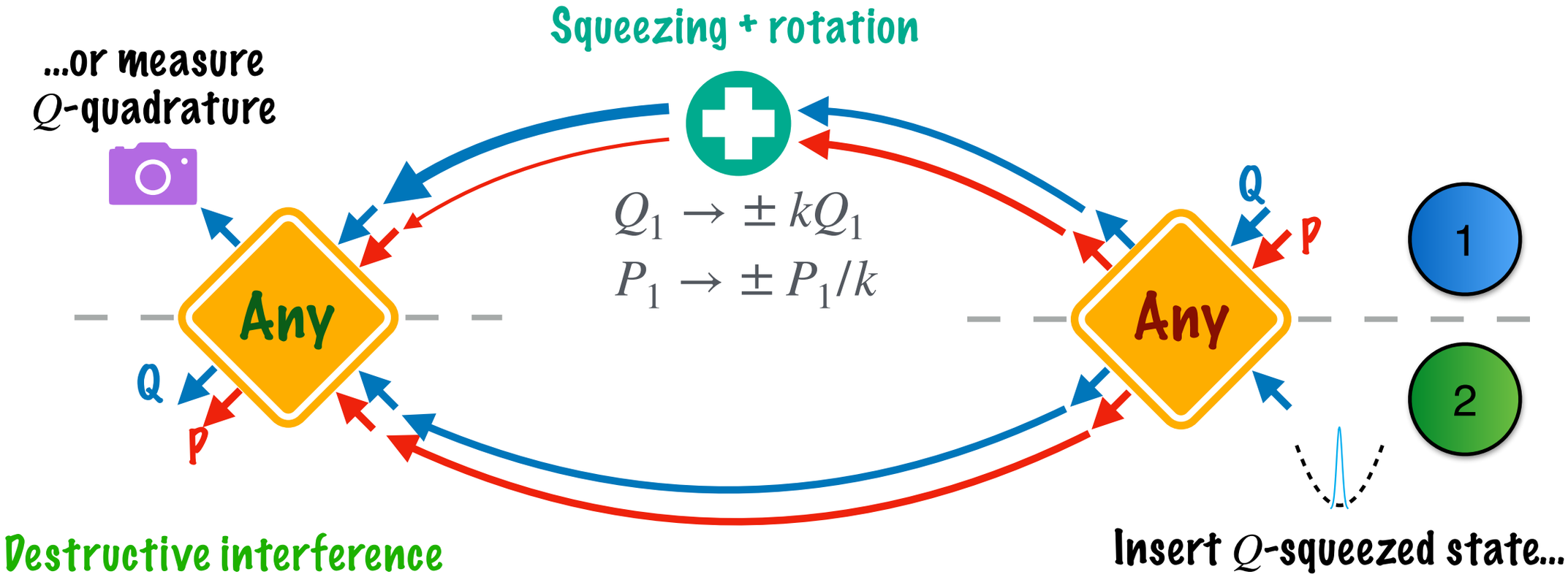

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Don't want injected squeezing or measurement?

Fong, Poon, **HKL**, *arXiv:2212.05134*

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Apply the imperfect interface one more time!

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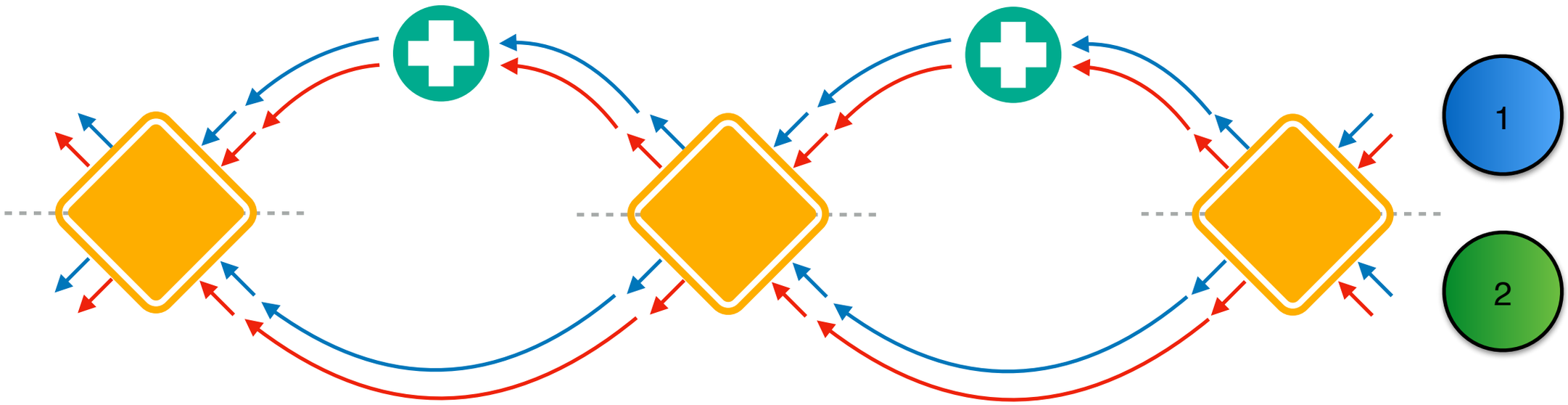

Any three interface = perfect swap

Fong, Poon, **HKL**, *arXiv:2212.05134*

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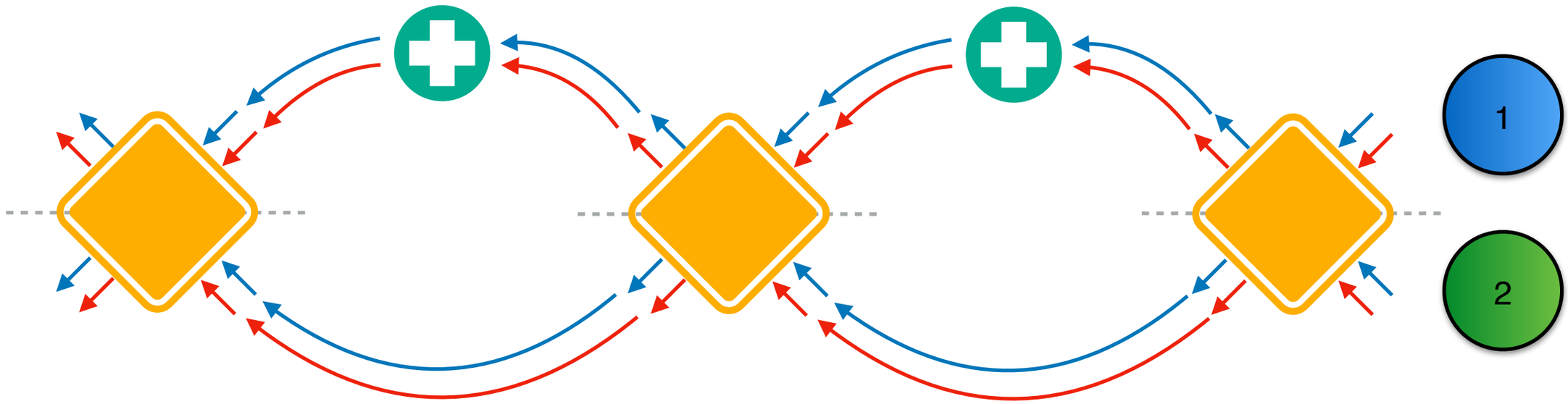


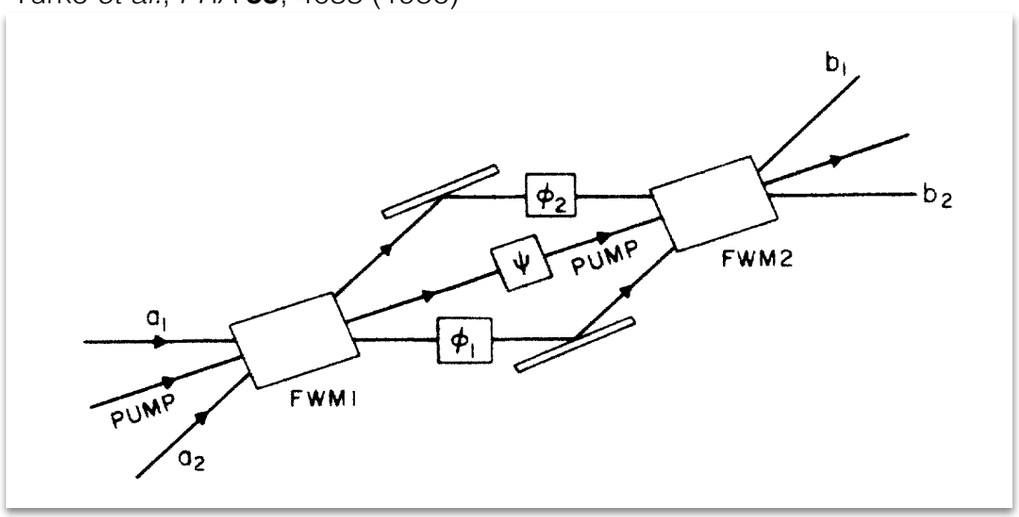
Any three interface = perfect swap

Necessary & sufficient

Fong, Poon, **HKL**, *arXiv:2212.05134*

Interface other than perfect swap?

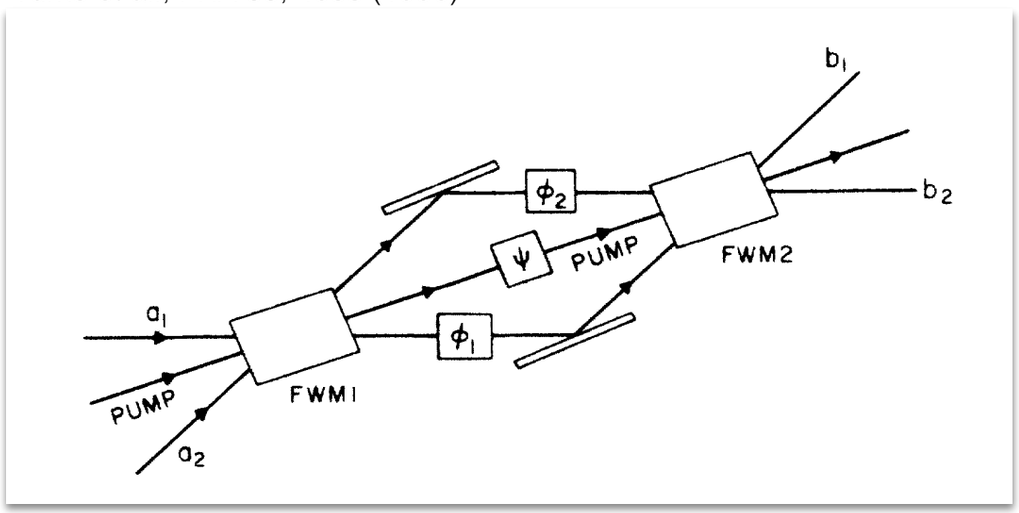
Yurke *et al.*, *PRA* **33**, 4033 (1986)



Two-mode-squeezing for SU(1,1) interferometry

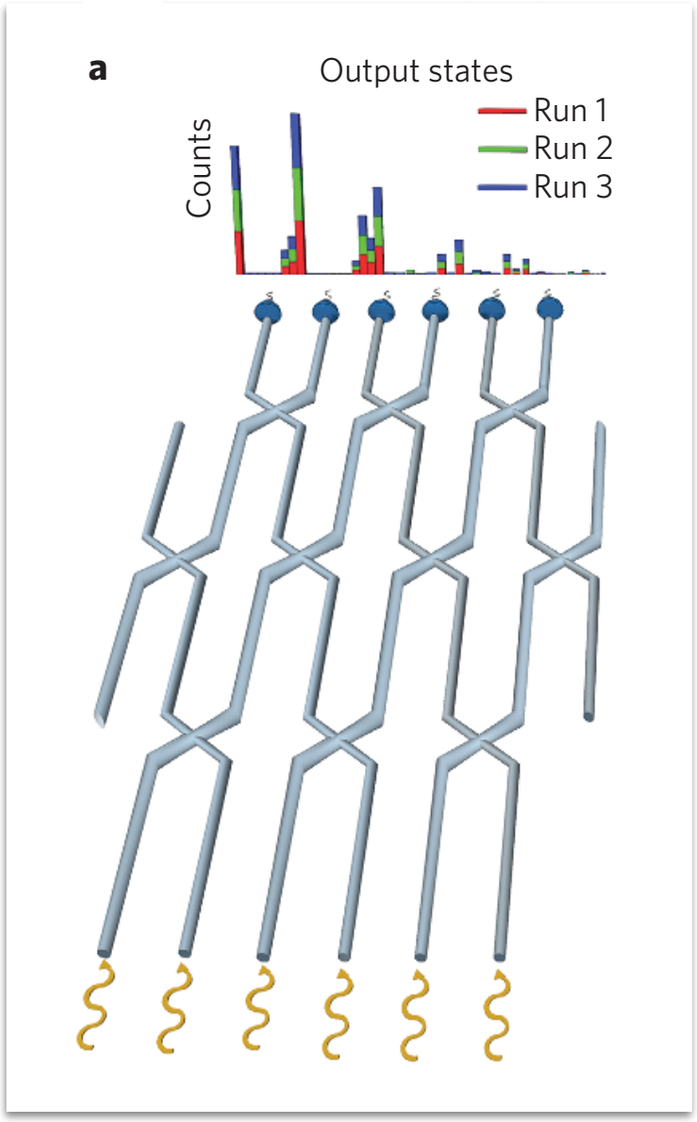
Interface other than perfect swap?

Yurke *et al.*, *PRA* **33**, 4033 (1986)



Two-mode-squeezing for SU(1,1) interferometry

Huh *et al.*, *Nat. Photonics* **9**, 615 (2015)



Beam-splitters for boson-sampling

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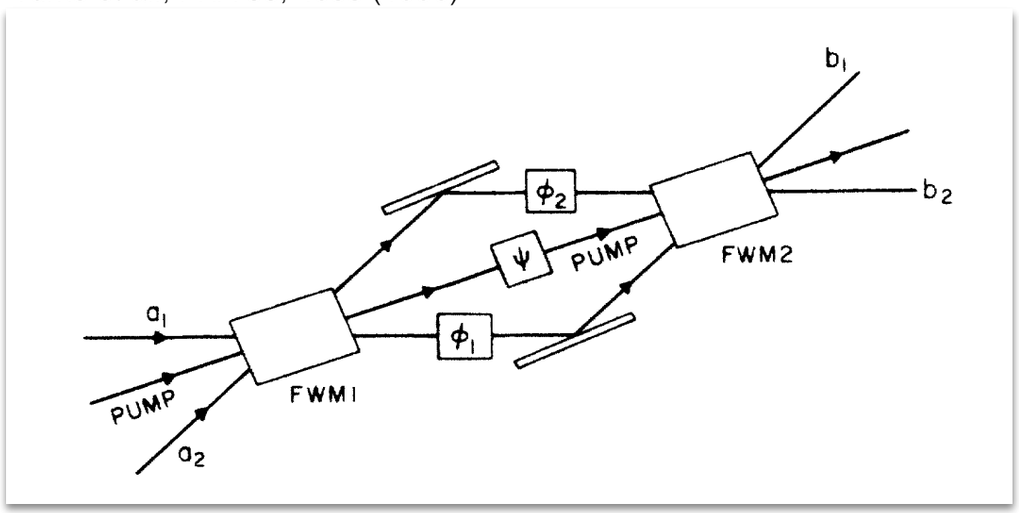

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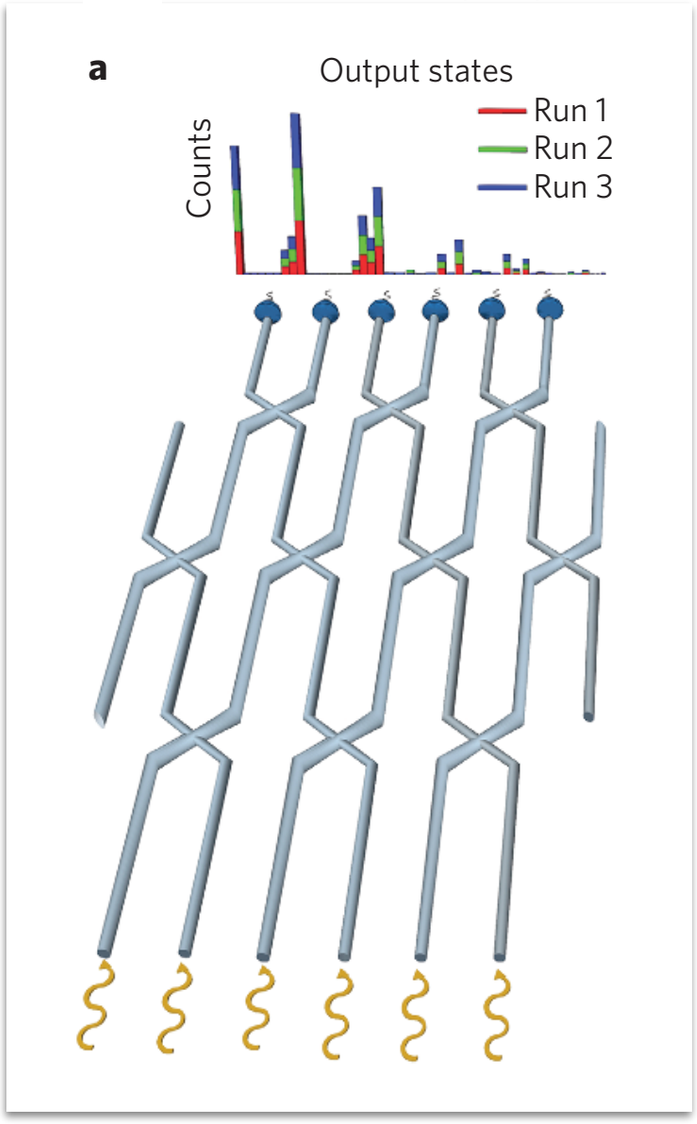
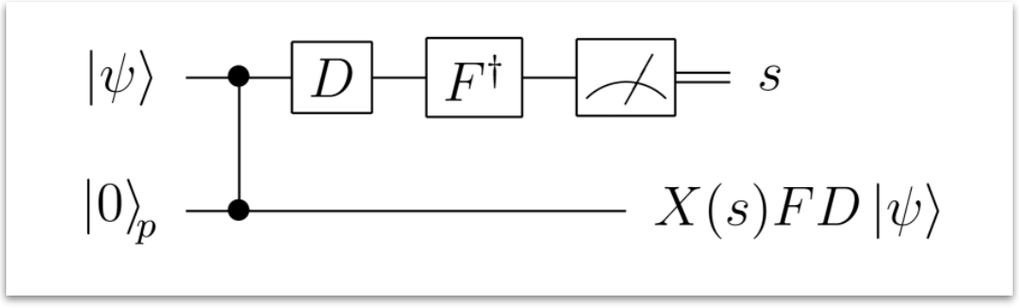


Beam-splitters for boson-sampling

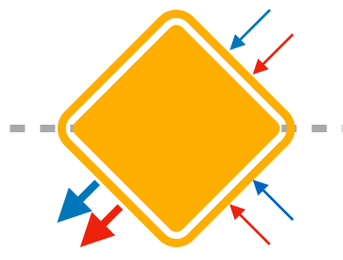
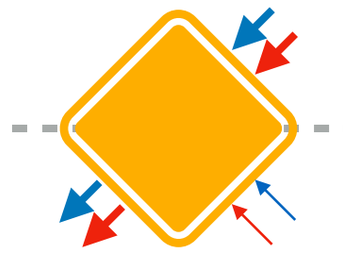
Menicucci *et al.*, *PRL* **97**, 110501 (2006)



QND gate for CV quantum computing

Interface other than perfect swap

	Local	QND gate	Transmitted: 2 Reflected: 2	NEW SWAP+QND	SWAP
Transmission strength χ	$\chi = 0$	$\chi = 0$	$\chi \neq 0$	$\chi = 1$	$\chi = 1$

Two-mode squeezing	Beam splitter	NEW SWAP+TMS
		
$0 > \chi$	$1 > \chi > 0$	$\chi > 1$

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	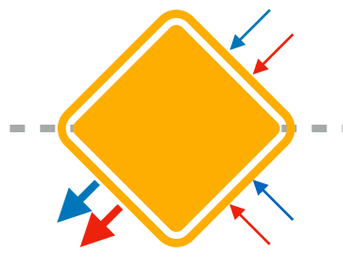	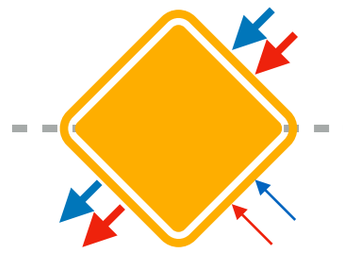
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Two interfaces are interconvertible iff they have same χ

Interface other than perfect swap

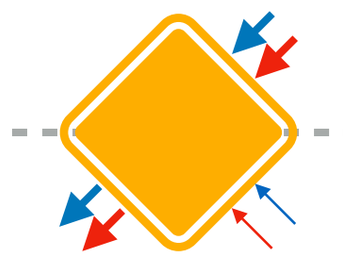
Local	QND gate	Transmitted: 2 Reflected: 2	NEW SWAP+QND	SWAP
$\chi = 0$	$\chi = 0$	$\chi \neq 0$	$\chi = 1$	$\chi = 1$

Transmission strength χ

Determinant

$$\begin{pmatrix} T_{QQ} & T_{QP} \\ T_{PQ} & T_{PP} \end{pmatrix}$$

Transmission matrix

Two-mode squeezing	Beam splitter	NEW SWAP+TMS
		
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Two interfaces are interconvertible iff they have same χ

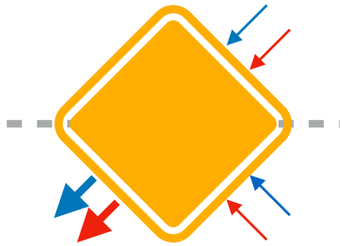
Beam-splitter

$$\begin{pmatrix} \sin\theta & 0 \\ 0 & \sin\theta \end{pmatrix}$$

Transmission matrix

$$\chi_{BS} = \sin^2\theta$$

Beam-splitting angle



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$$\begin{pmatrix} \sin\theta & 0 \\ 0 & \sin\theta \end{pmatrix}$$

Transmission matrix

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Beam-splitting angle

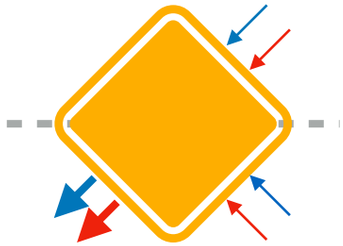
Two-mode squeezing
(Phase insensitive amplification)

$$\begin{pmatrix} \sinh r & 0 \\ 0 & -\sinh r \end{pmatrix}$$

Transmission matrix

$$\chi_{TMS} = -\sinh^2 r$$

Squeezing strength



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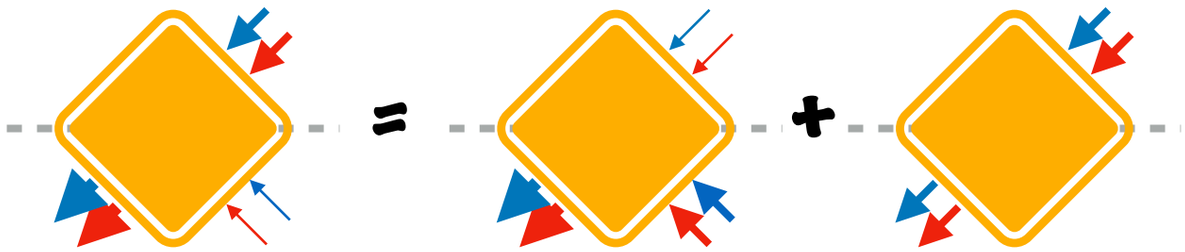
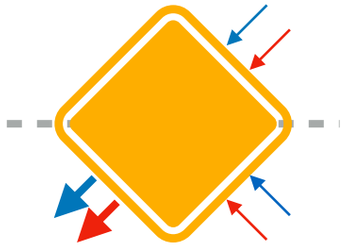
Squeezing strength



Swapped two-mode squeezing

$$\chi_{STMS} = 1 - \chi_{TMS} = \cosh^2 r$$

Squeezing strength



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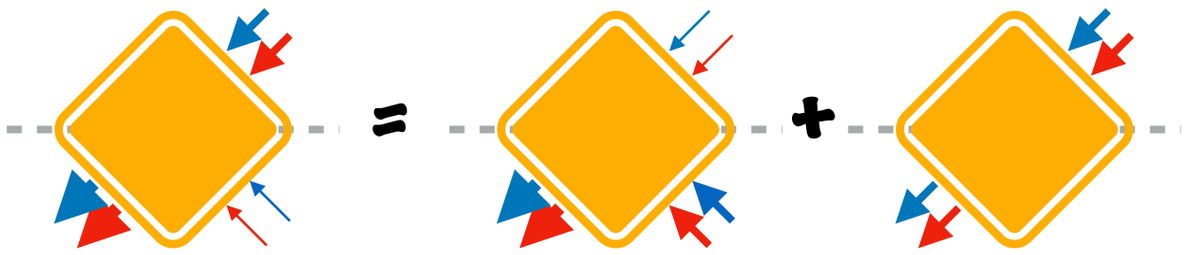


Swapped two-mode squeezing

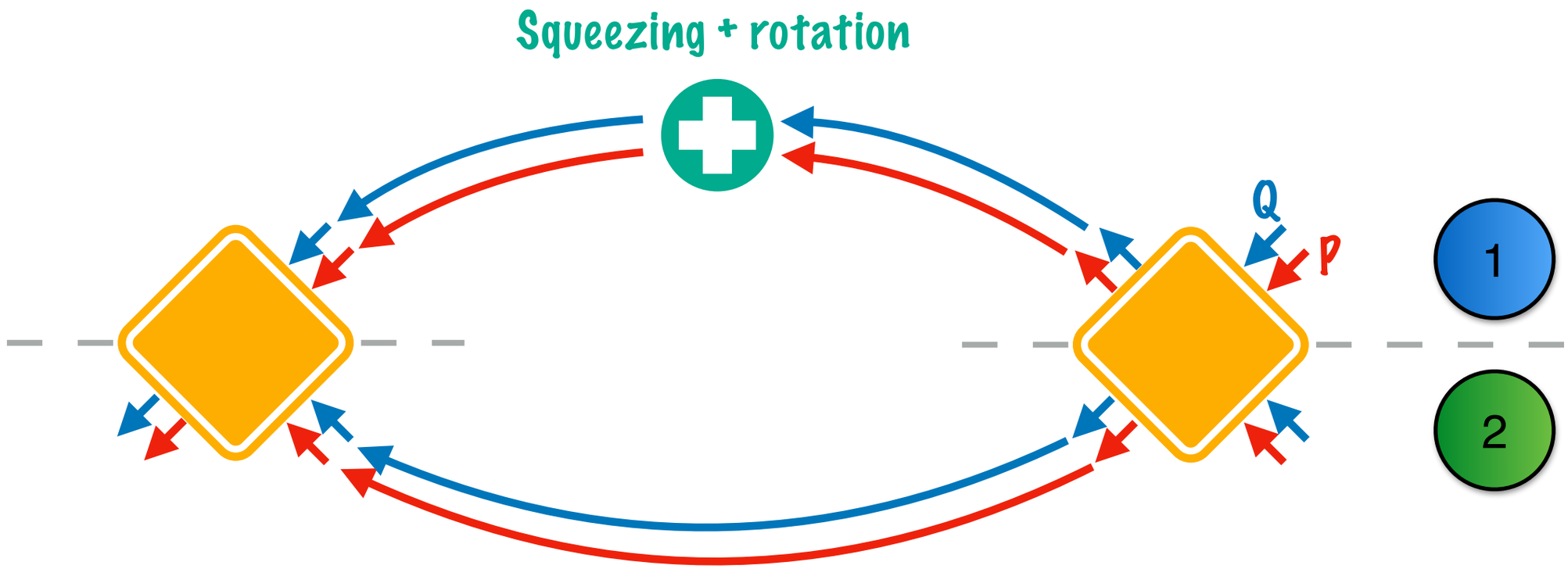
$$\chi_{STMS} = 1 - \chi_{TMS} = \cosh^2 r$$

Squeezing strength

Unified parameter to characterize all interface

Engineering arbitrary interface except SWAP

= engineer interface with arbitrary χ



Engineering arbitrary interface except SWAP

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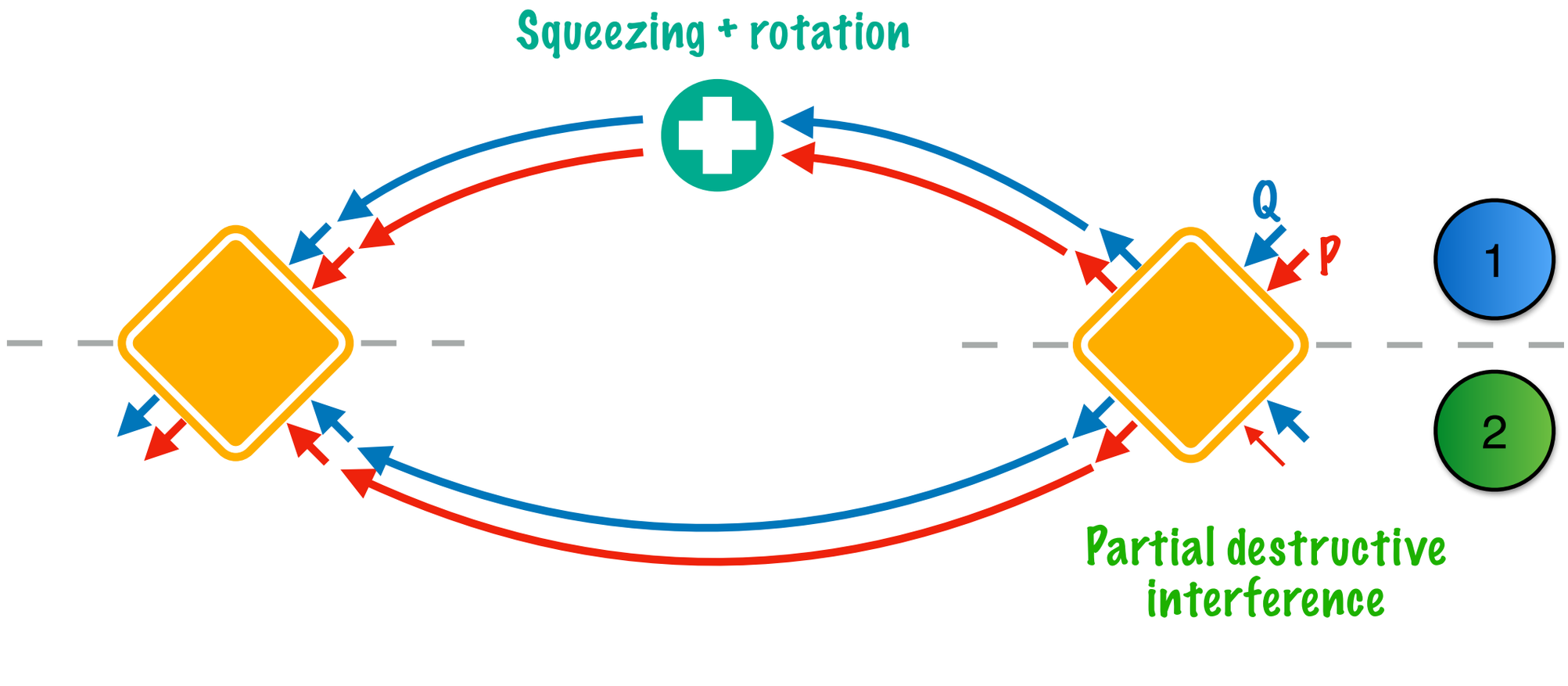

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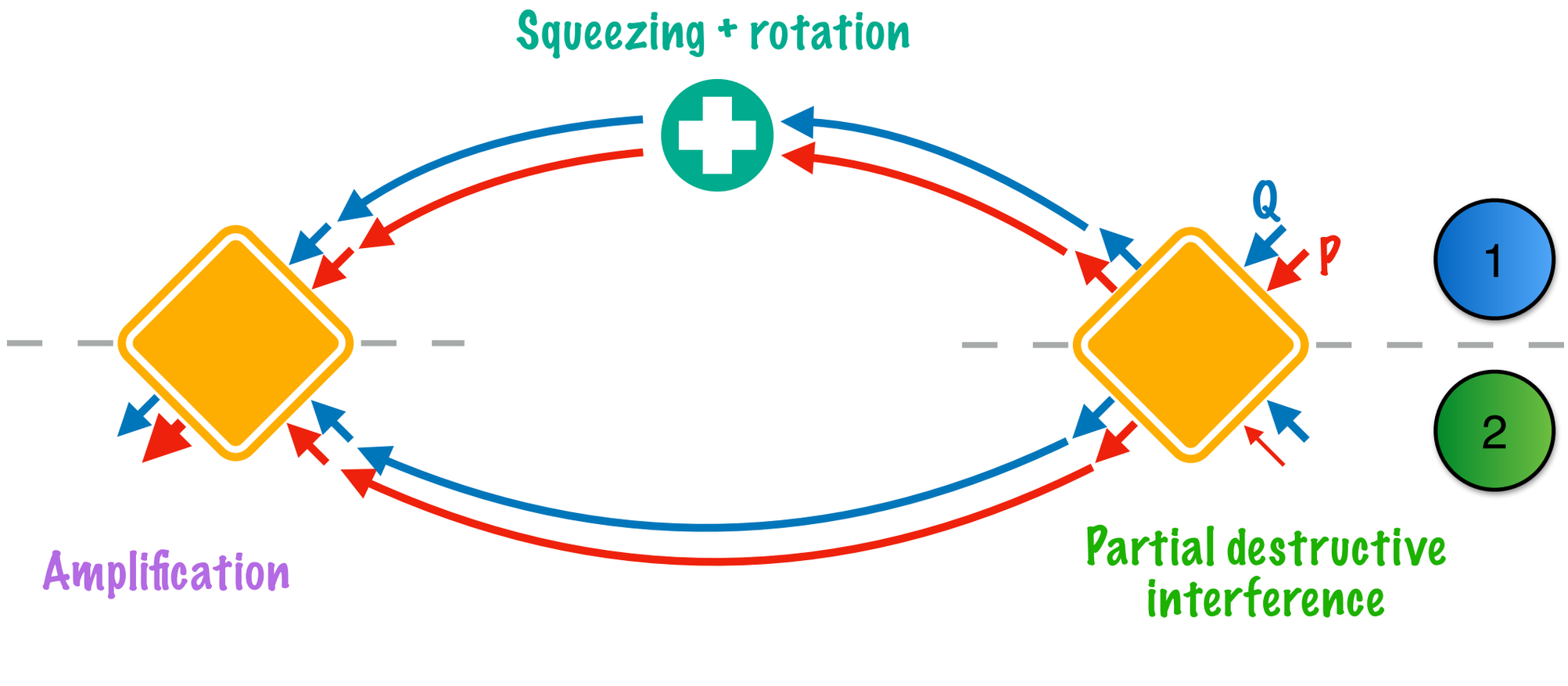

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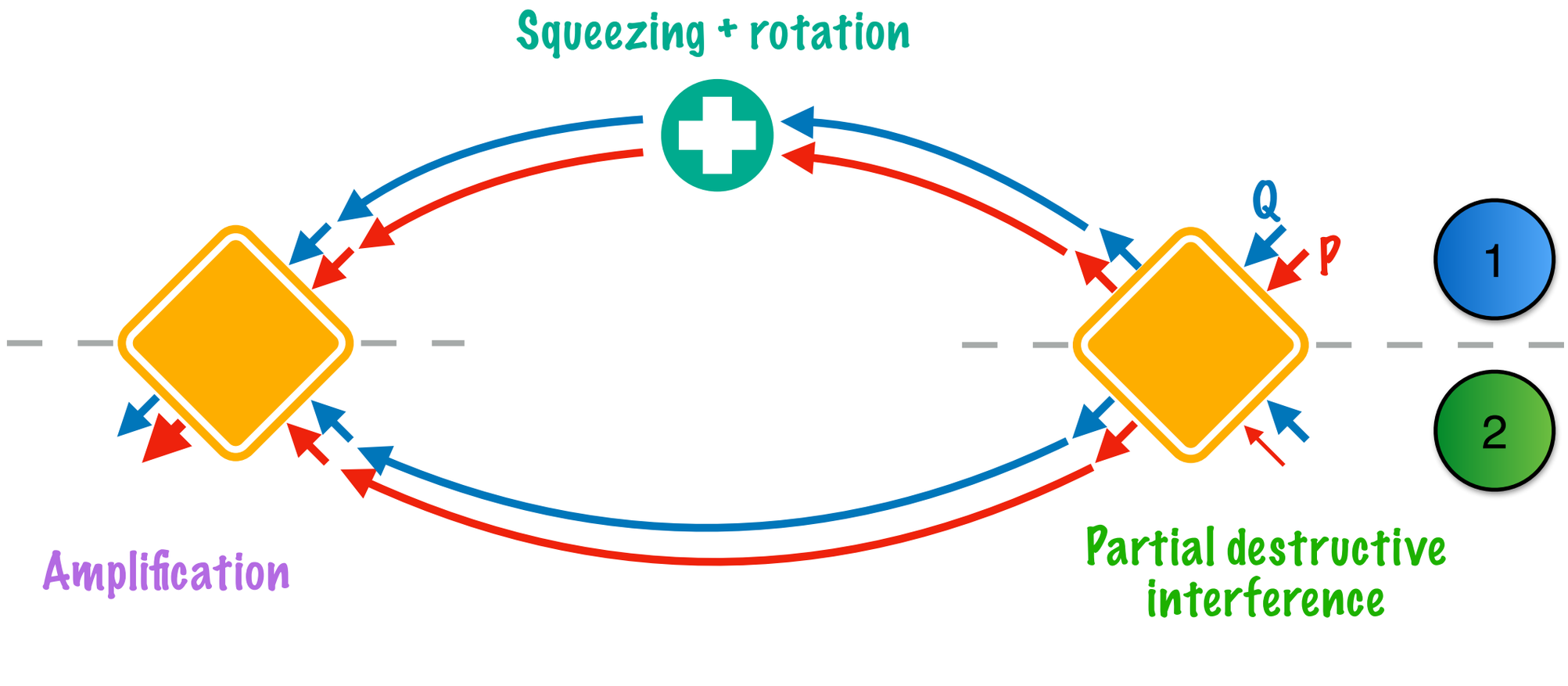
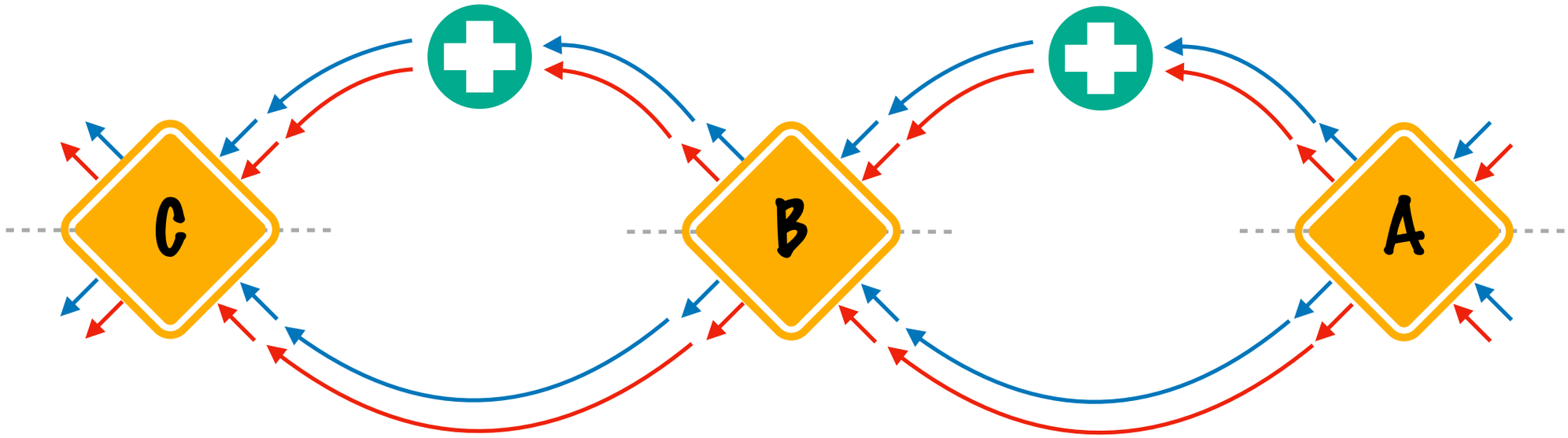


Only two interface is required

SWAP engineering revisited

Any three interface = perfect swap



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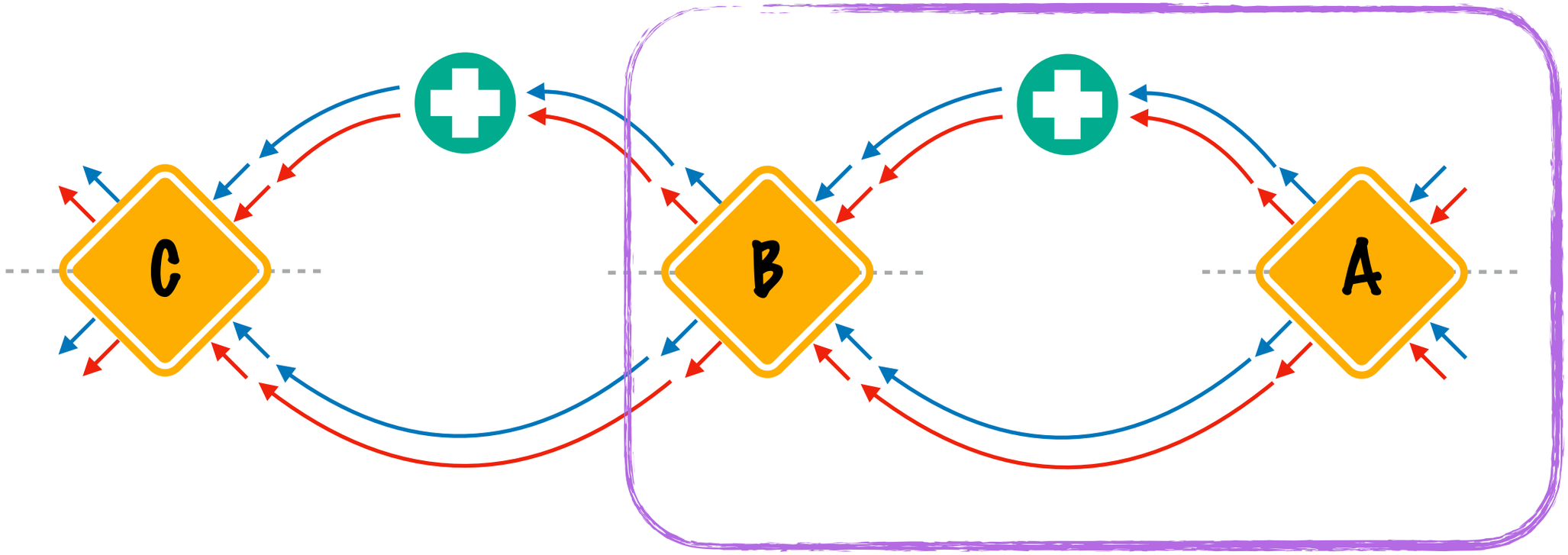

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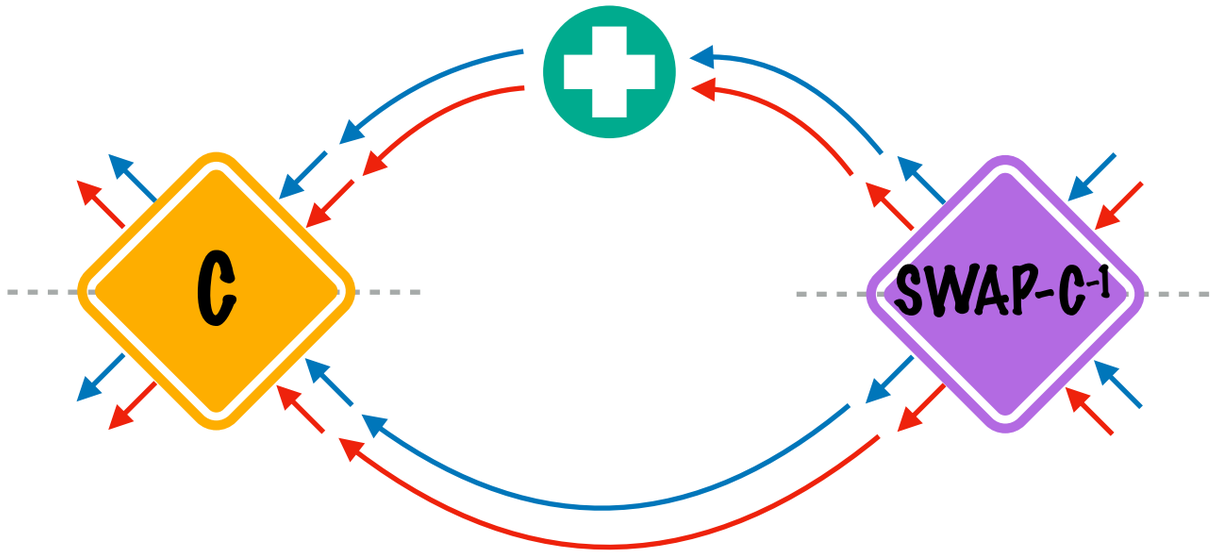

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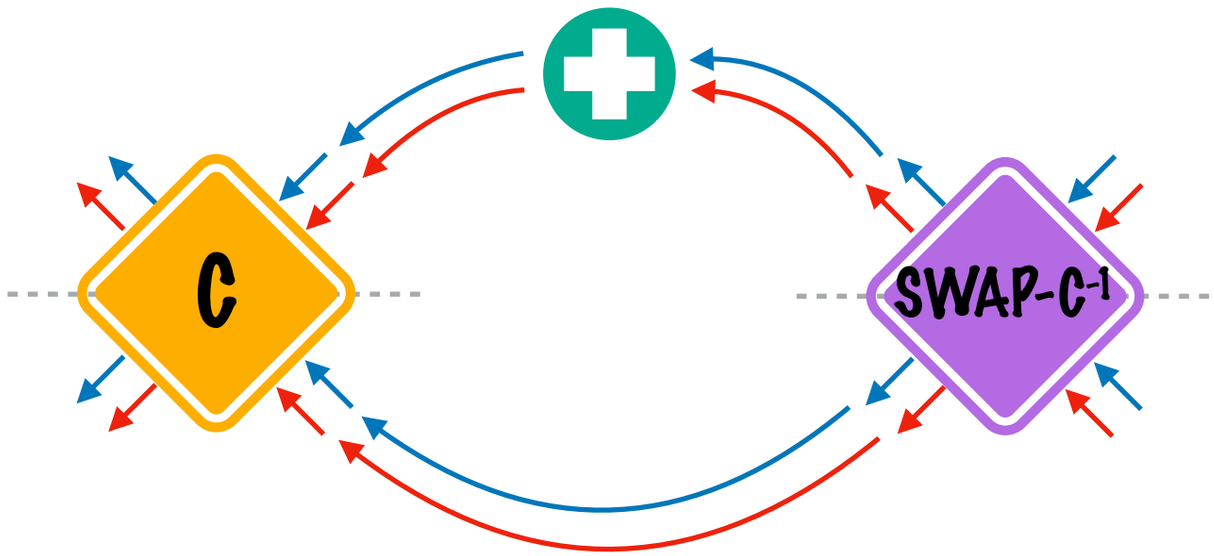
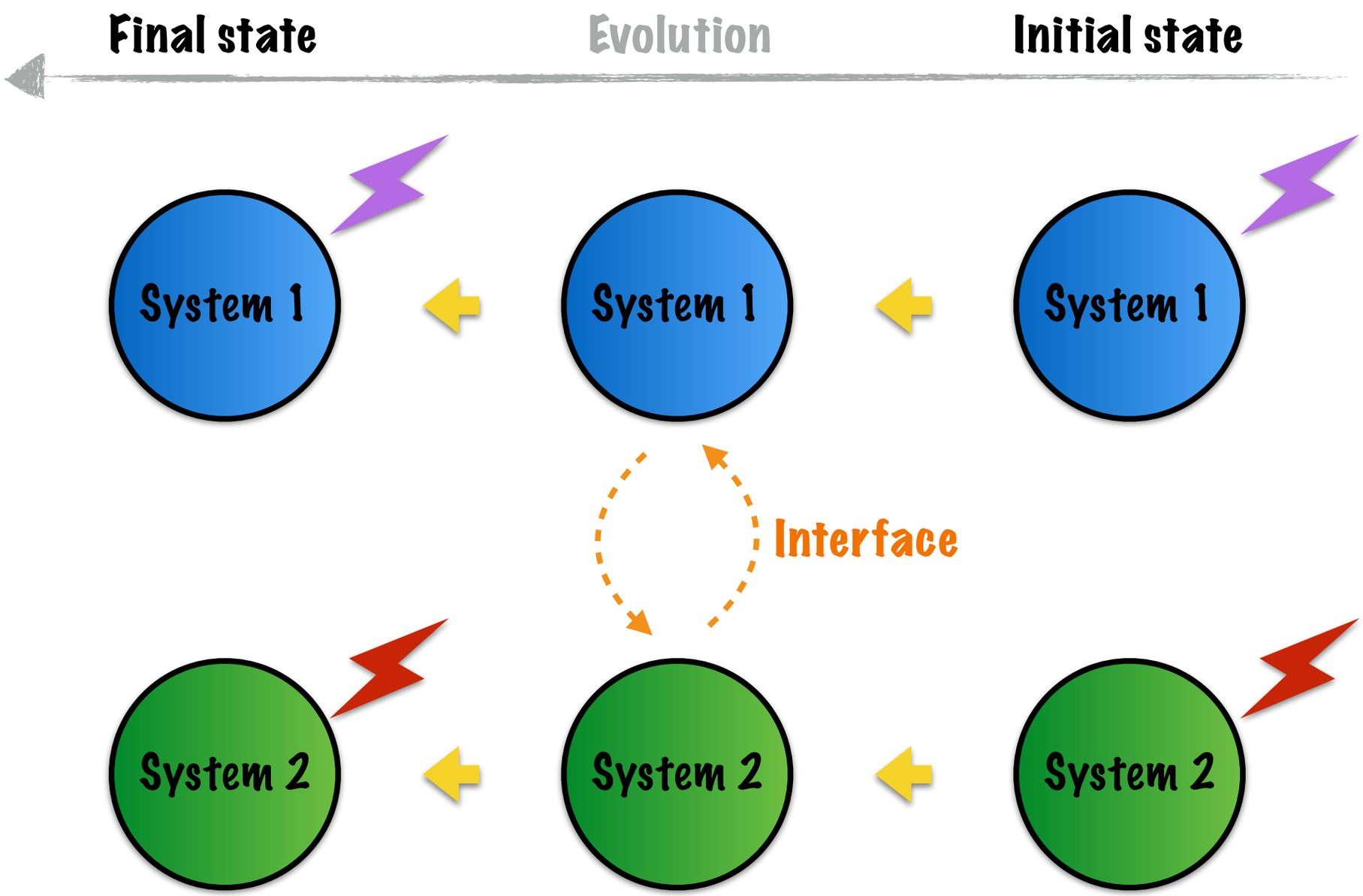
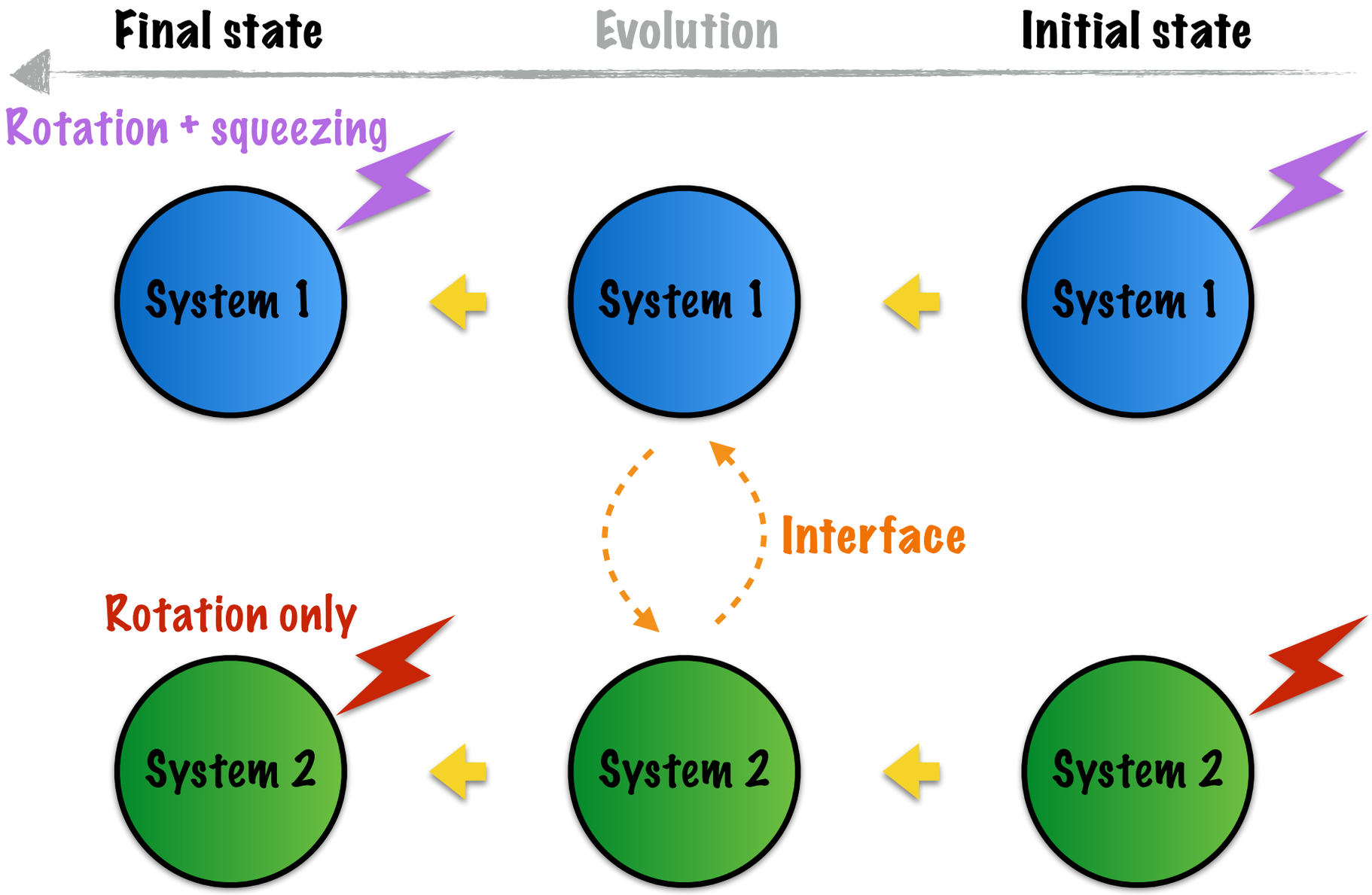


Optimal

Squeezing restriction



Squeezing restriction



Squeezing restriction

Final state

Evolution

Initial state

Rotation + squeezing

System 1

System 1

System 1

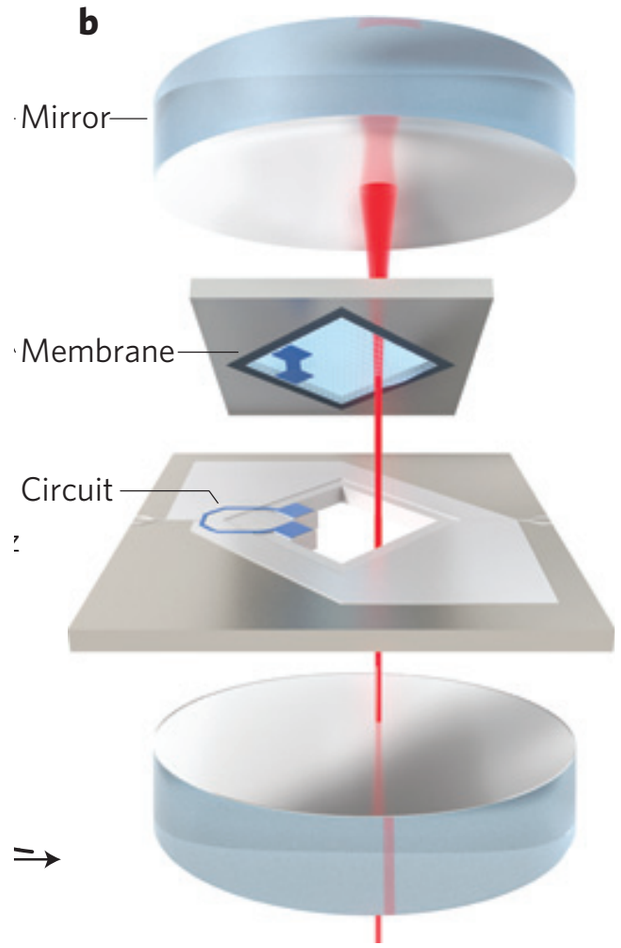
Interface

Rotation only

System 2

System 2

System 2



Optomechanical transducer

Andrews et al, Nat. Phys. 10, 321 (2014)

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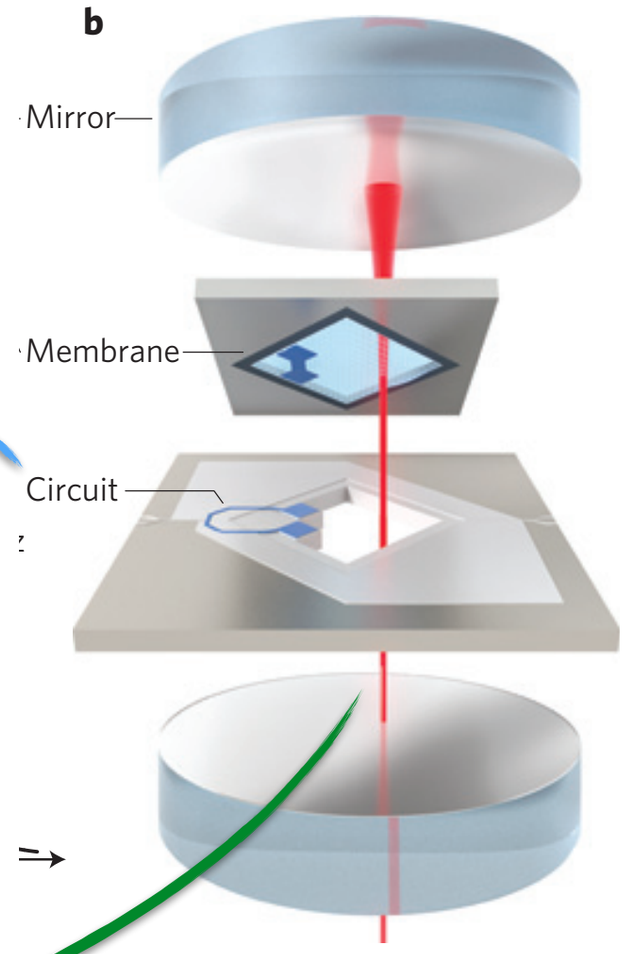

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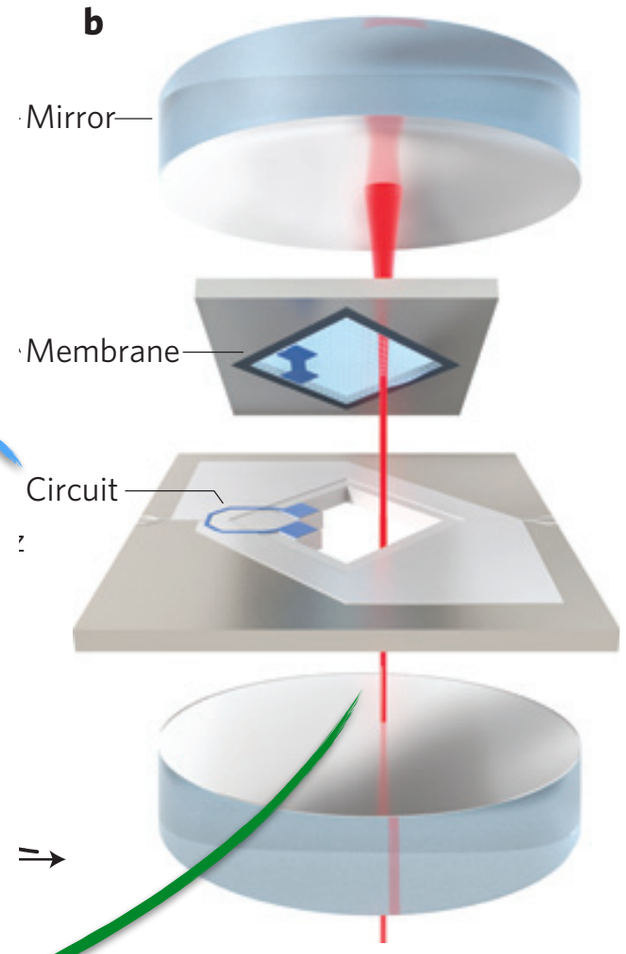

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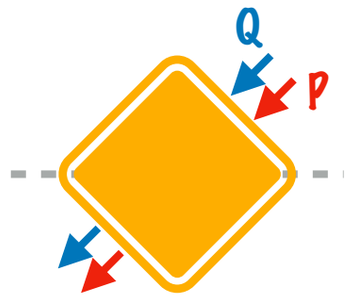
Andrews et al, Nat. Phys. 10, 321 (2014)

How does squeezing restriction affect interface engineering?

1. Modified Classification

	Local	QND gate	BS, TMS, sTMS	SWAP+QND	SWAP
					
Transmitted quadratures	0	1	2	2	2
Reflected quadratures	2	2	2	1	0
Transmission strength	$\chi = 0$	$\chi = 0$	$\chi \neq 0,1$	$\chi = 1$	$\chi = 1$

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					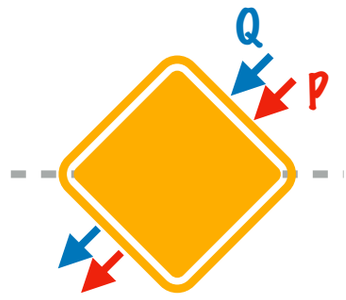
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Irreducible squeezing Λ

Irreducible Shearing κ

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					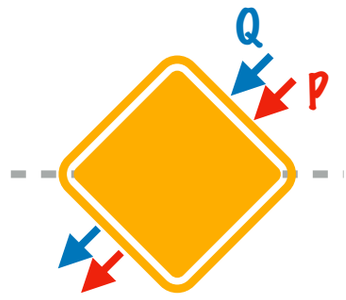
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Restricted mode

$$\begin{pmatrix} Q_2(T) \\ P_2(T) \end{pmatrix} = \begin{pmatrix} T_{QQ} & T_{QP} \\ T_{PQ} & T_{PP} \end{pmatrix} \begin{pmatrix} Q_1(0) \\ P_1(0) \end{pmatrix} + \begin{pmatrix} R_{QQ} & R_{QP} \\ R_{PQ} & R_{PP} \end{pmatrix} \begin{pmatrix} Q_2(0) \\ P_2(0) \end{pmatrix}$$

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					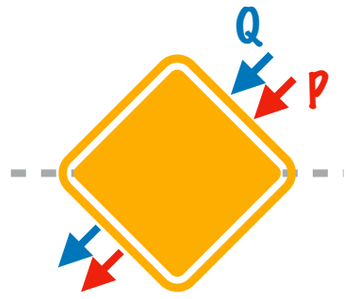
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$$\propto \begin{pmatrix} \Lambda & 0 \\ 0 & \Lambda^{-1} \end{pmatrix}$$

Ratio of singular values

1. Modified Classification

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	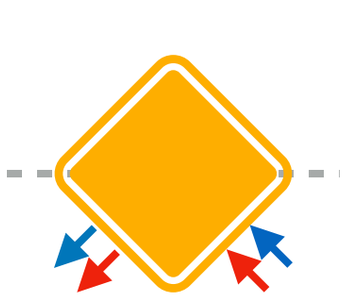	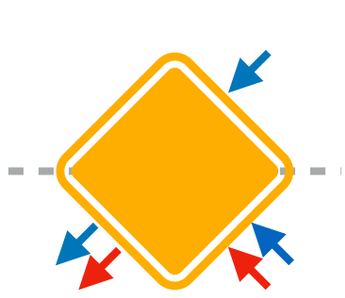	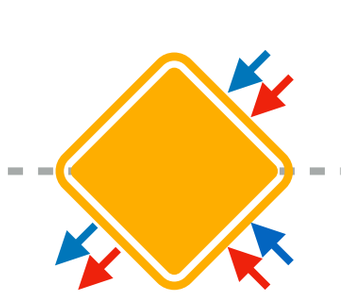	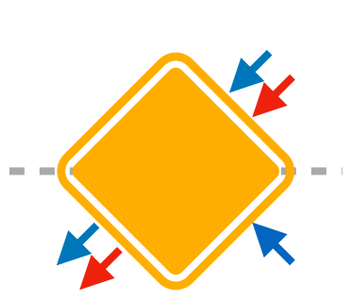	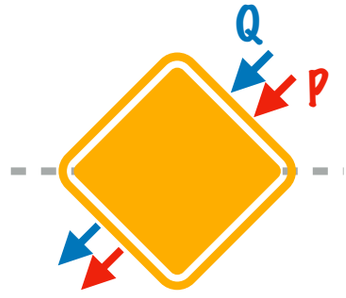
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Irreducible Shearing κ

Restricted mode

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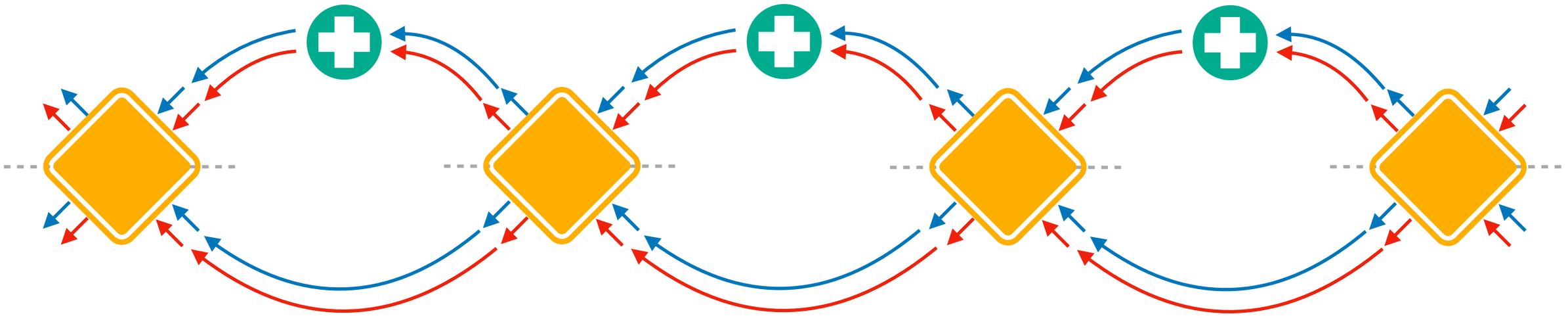
Ratio of singular values

2. More parameters to engineer

Four interface protocol



Fong, Poon, **HKL**, *arXiv:2212.05134*

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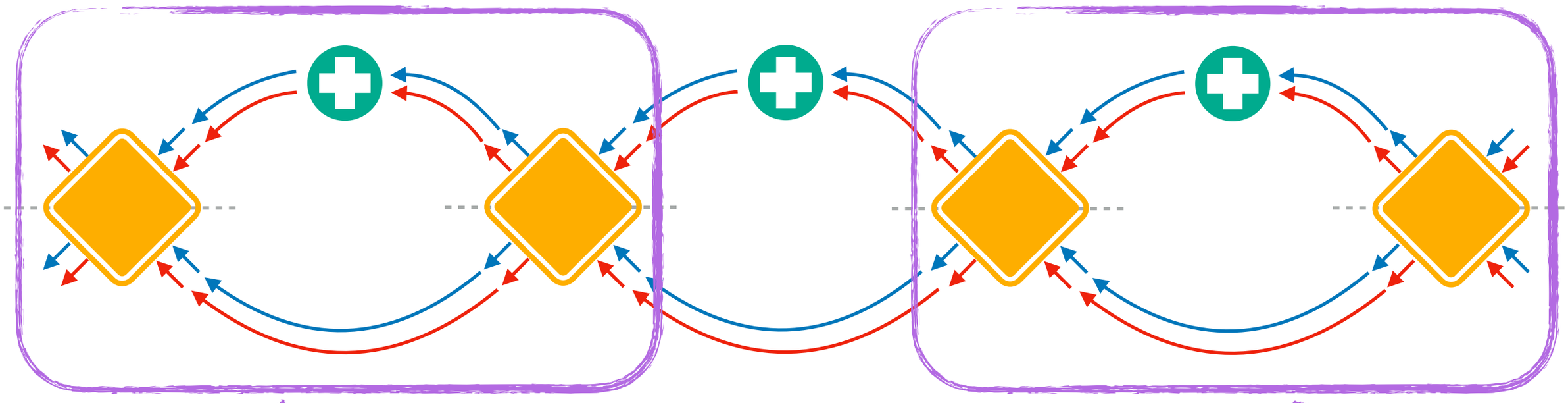


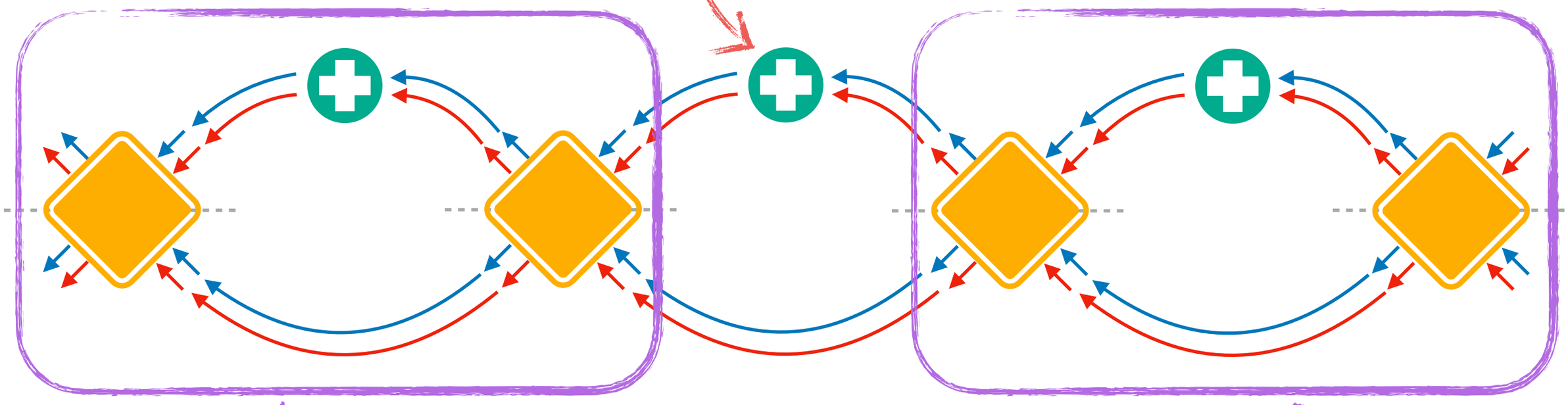
Determine overall transmission strength

Fong, Poon, **HKL**, *arXiv:2212.05134*

2. More parameters to engineer

Four interface protocol

Tune irreducible squeezing and shearing



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Bosonic Quantum Interface: Characterization, Engineering, and Application

SFU

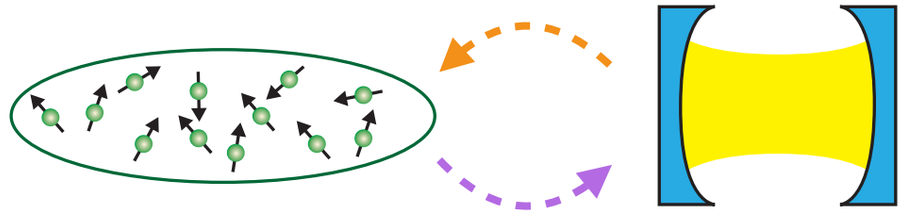
Kero Lau (kero_lau@sfu.ca)

HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)
Fong, Poon, **HKL**, *arXiv:2212.05134*

Bosonic Quantum Interface: Characterization, Engineering, and Application

SFU

Interface: connect quantum systems & process quantum information



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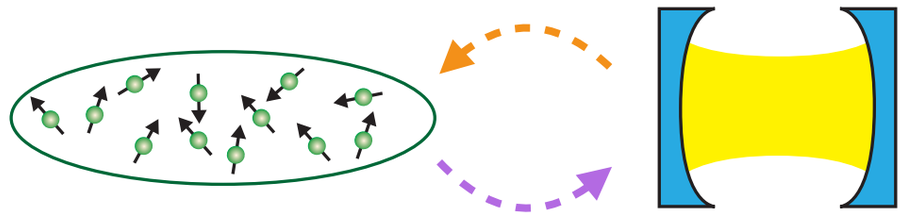

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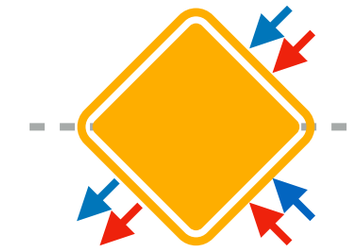
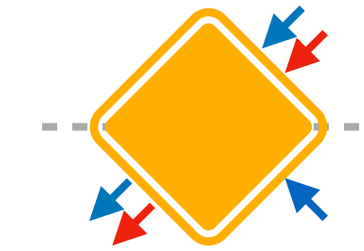
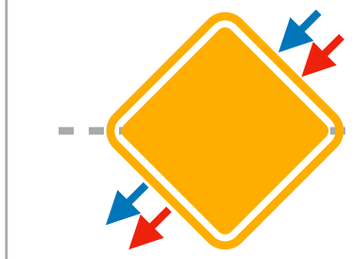
				

Transmitted & reflected quadratures, transmission strength

Squeezing restriction: irreducible squeezing, irreducible shearing

Kero Lau (kero_lau@sfu.ca)

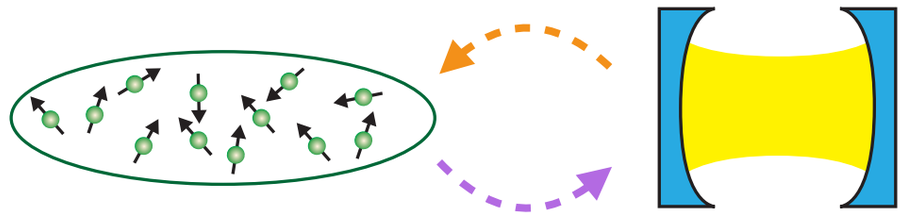
HKL & Clerk, *npj Quant. Inf.* **5**, 31 (2019)

Fong, Poon, **HKL**, *arXiv:2212.05134*

Bosonic Quantum Interface: Characterization, Engineering, and Application

SFU

Interface: connect quantum systems & process quantum information



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	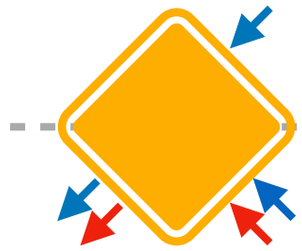	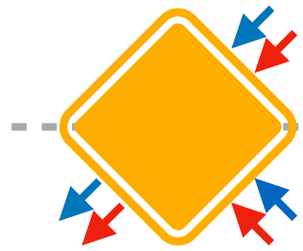	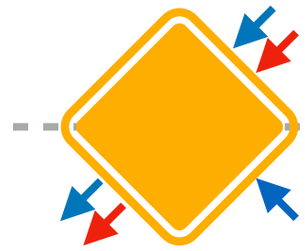	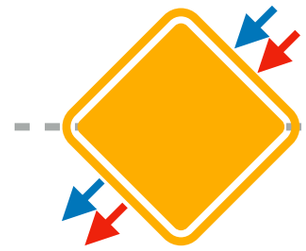

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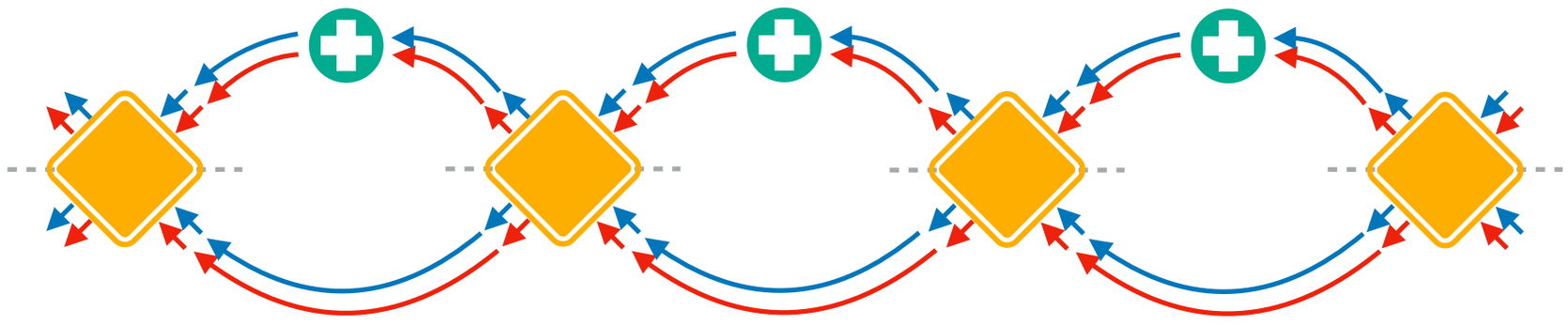
Any interface can be engineered by cascading at most 5 fixed interfaces



Kero Lau (kero_lau@sfu.ca)

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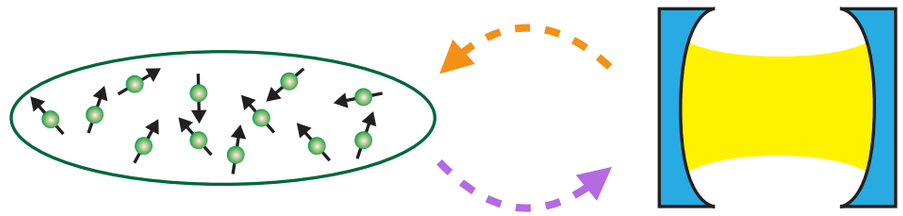

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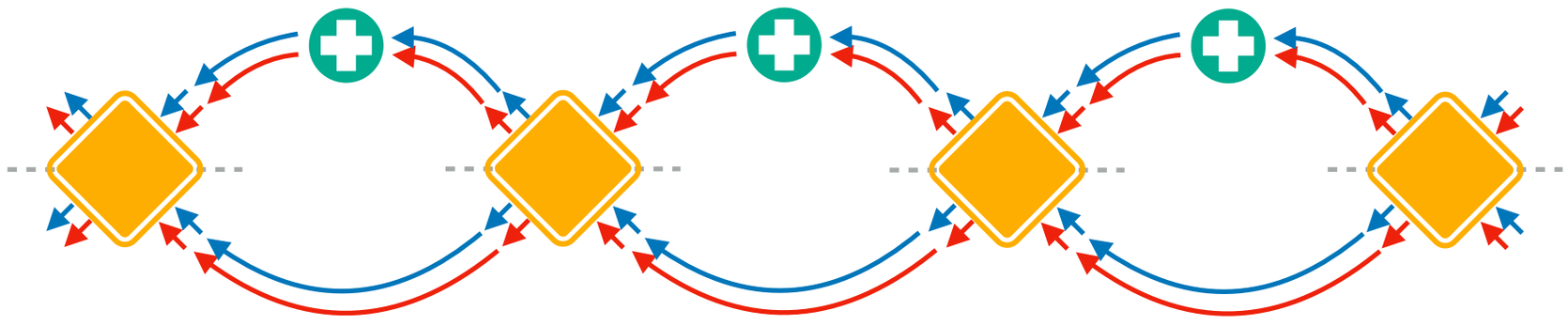

Kero Lau (kero_lau@sfu.ca)

Postdoc & grad student positions available

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