Jessica Bavaresco

Senior Postdoc Fellow (*Maître Assistante*)
University of Geneva

Higher-order quantum computation

CNRS Concours 06/02

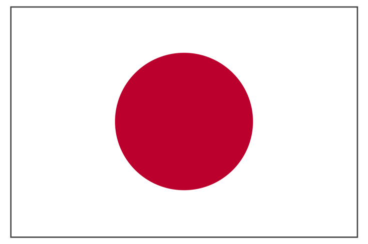
12 April 2024

Academic trajectory

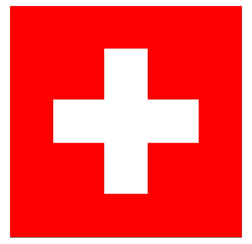
[2012]  **Bachelor's internship** at Lafayette College, **USA**

[2014-2016]  **Master's** at UFMG, **Brazil**

[2016-2021]  **PhD** at University of Vienna, **Austria**

[2019]  **PhD internship** at University of Tokyo, **Japan**

[2021-2022]  **Postdoc** at IQOQI Vienna, **Austria**

[2022-]  **Postdoc** at University of Geneva, **Switzerland**
Senior postdoc fellow at University of Geneva

Academic achievements

[2012]	**Bachelor's internship** at Lafayette College, **USA**
[2014-2016]	**Master's** at UFMG, **Brazil**
[2016-2021]	**PhD** at University of Vienna, **Austria**
[2019]	**PhD internship** at University of Tokyo, **Japan**
[2021-2022]	**Postdoc** at IQOQI Vienna, **Austria**
[2022-]	**Postdoc** at University of Geneva, **Switzerland** **Senior postdoc fellow** at University of Geneva

PhD in June 2021

13 publications, 1 preprint
7 as first author
over 40 co-authors

2+1 invited conference talks
10+1 accepted conference talks
16+1 invited seminars

2 postdoc grants (MSCA and SNSF)
2 research grants
1 stipend
= ~630k EUR

Fonds national suisse

MARIE CURIE ACTIONS

1 conference steering committee
1 PhD thesis jury

Research experience

Quantum Information Science

BACHELOR'S | MASTER'S | PHD | POSTDOC

Molecular Dynamics Simulations

[NBB15] Phys. Rev. B(R)
[NB18] J. Chem. Phys.

Quantum Correlations

[BQG+17] Phys. Rev. A
[GBT+17] J. Math. Phys.

Quantum Entanglement

[SEM+17] **Nature Commun.**
[BVK+18] **Nature Physics**
[CEB+20] Phys. Rev. A
[YMM+22] Quantum

Indefinite Causal Order

[BAB+19] Quantum
[MBC22] Quantum
[CBW+23] Optica

Quantum Information Tasks

[BQM21] **Phys. Rev. Lett.**
[BQM22] J. Math. Phys.
[BLS+23] arXiv:2311.01513

Research experience

Quantum Information Science

Bachelor's	Master's	PhD			Postdoc
Computational Physics	Theoretical Physics	Experimental Quantum Optics	Mathematical Physics		Foundations of Quantum Computing
Molecular Dynamics Simulations	Quantum Correlations	Quantum Entanglement	Indefinite Causal Order		Quantum Information Tasks

[NBB15] Phys. Rev. B(R)
[NB18] J. Chem. Phys.

[BQG+17] Phys. Rev. A
[GBT+17] J. Math. Phys.

[SEM+17] **Nature Commun.**
[BVK+18] **Nature Physics**
[CEB+20] Phys. Rev. A
[YMM+22] Quantum

[BAB+19] Quantum
[MBC22] Quantum
[CBW+23] Optica

[BQM21] **Phys. Rev. Lett.**
[BQM22] J. Math. Phys.
[BLS+23] arXiv:2311.01513

Perspective

Quantum computing

how can we efficiently manipulate and process quantum data?

Higher-order quantum computing

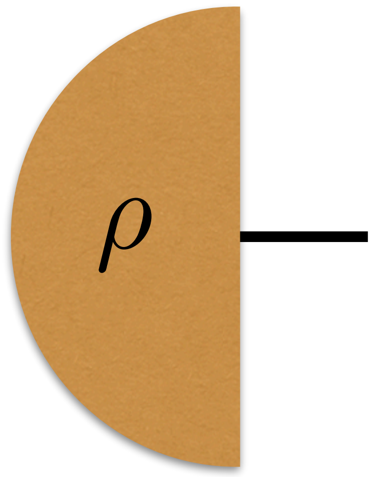
how can we efficiently manipulate and process quantum **functions**?

Formalism: Higher-order operations

Linear algebra:

quantum data:

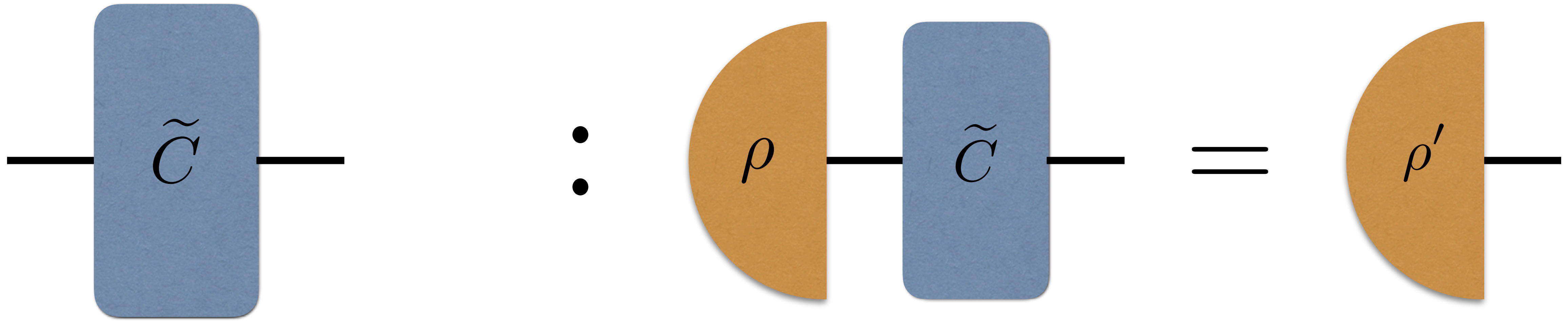
quantum states



$\rho \in \mathcal{L}(\mathcal{H}_{\text{in}})$

quantum functions:

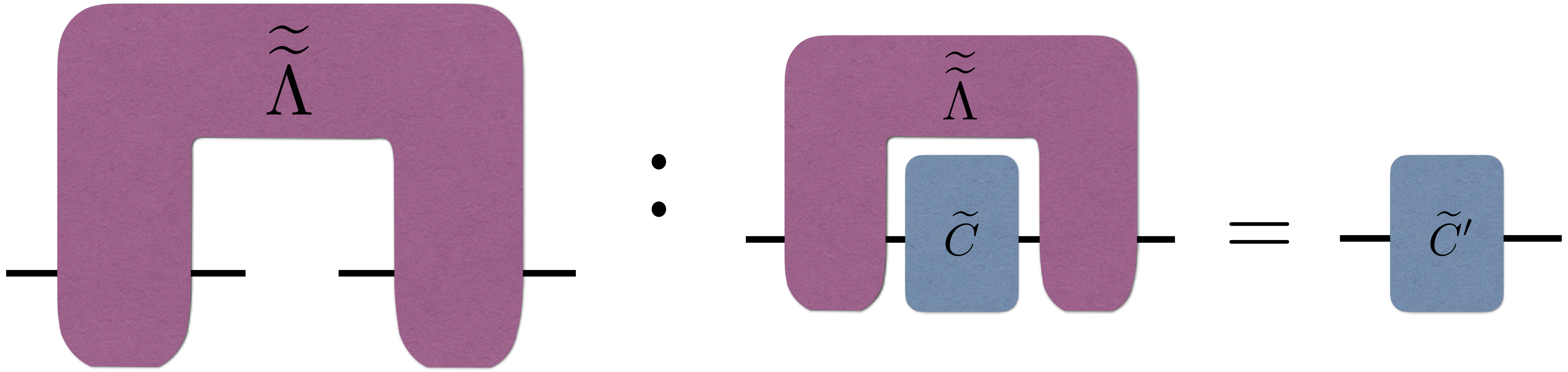
quantum operations (channels)



$\widetilde{C} : \mathcal{L}(\mathcal{H}_{\text{in}}) \to \mathcal{L}(\mathcal{H}_{\text{out}})$

higher-order quantum operations:

quantum processes



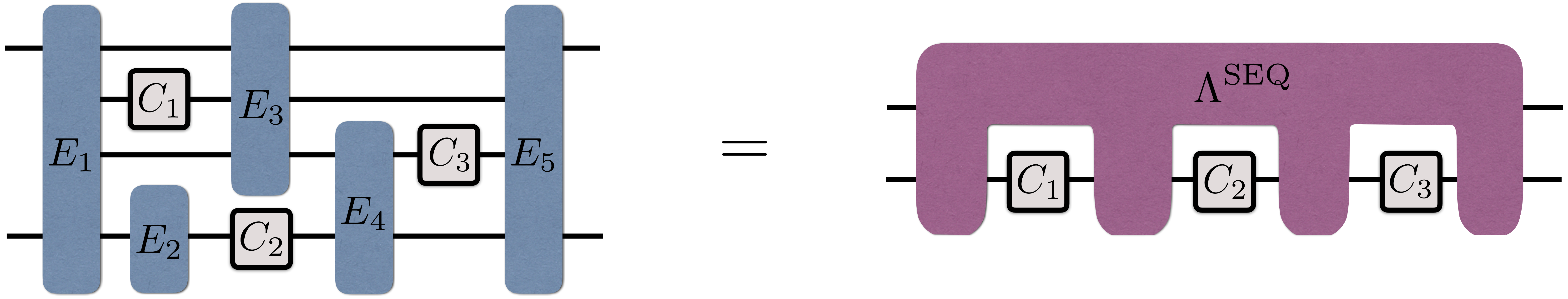
$\widetilde{\widetilde{\Lambda}} : [\mathcal{L}(\mathcal{H}_{\text{in}}) \to \mathcal{L}(\mathcal{H}_{\text{out}})]$
$\to [\mathcal{L}(\mathcal{H}_{\text{in}'}) \to \mathcal{L}(\mathcal{H}_{\text{out}'})]$

"functions of functions"

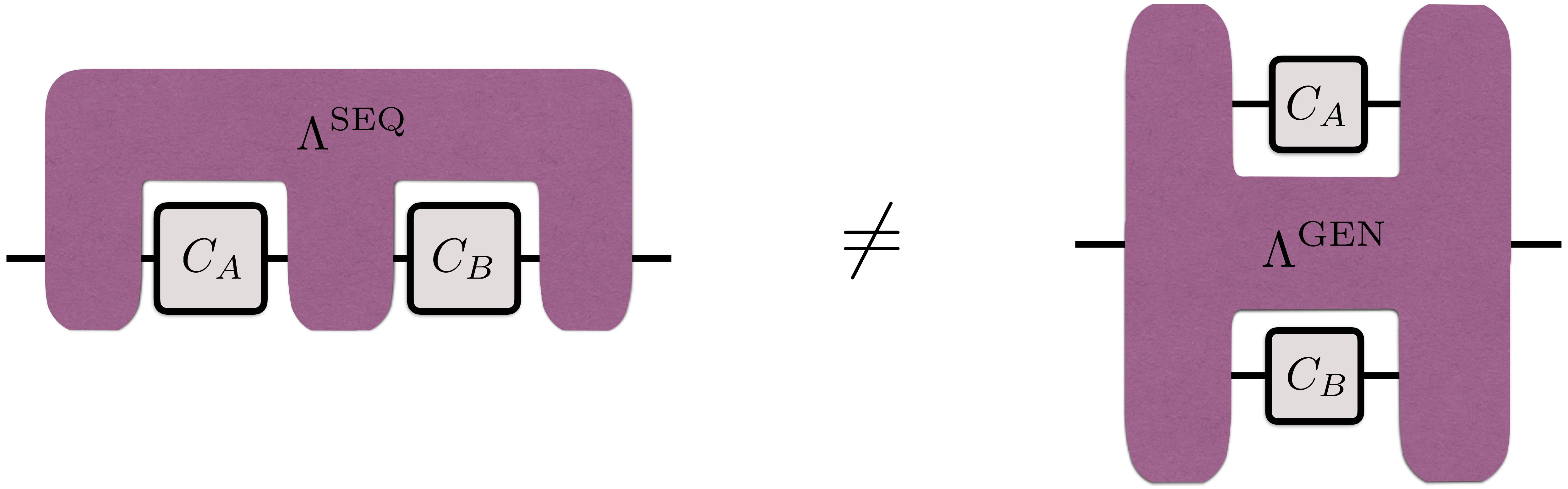
Jessica Bavaresco

Key features: Higher-order operations

1) Higher-order quantum operations efficiently describe quantum circuits

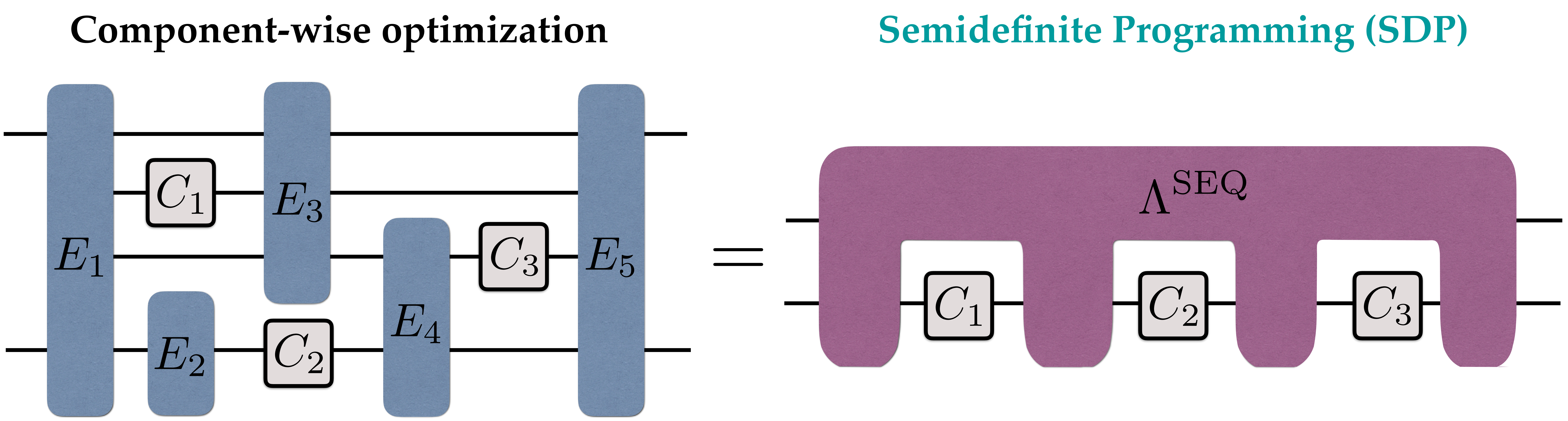


2) Higher-order quantum operations go beyond the quantum circuit model



Key features: Higher-order operations

1) Higher-order quantum operations efficiently describe quantum circuits



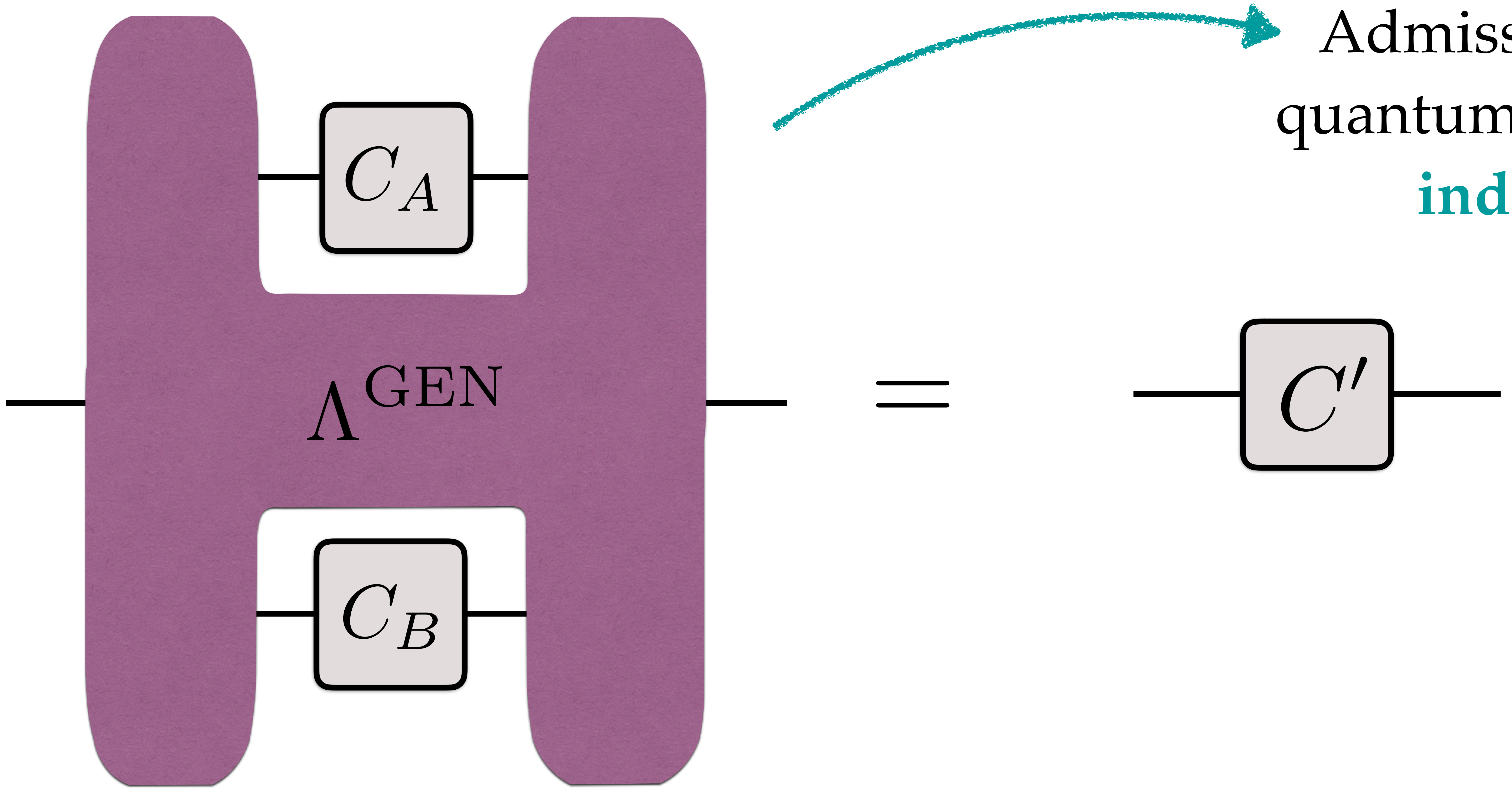
Semidefinite Programming (SDP) ⟷ **Quantum Computation**

Linear Programming (LP) ⟷ **Classical Computation**

Key features: Higher-order operations

2) Higher-order quantum operations go beyond the quantum circuit model

$$(C_A, C_B) \mapsto C'$$



Admissible transformations of quantum operations may have an **indefinite causal order**

Key features: Higher-order operations

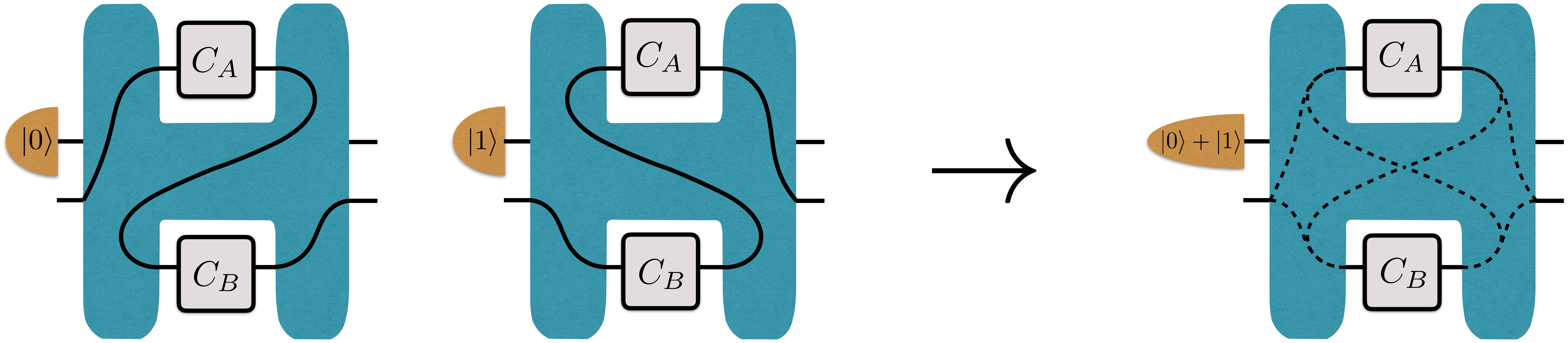
2) Quantum higher-order operations go beyond the quantum circuit model

CLASSICAL	QUANTUM	HIGHER-ORDER QUANTUM
data (bits)	quantum data (qbits)	quantum data (qbits)
gates	quantum gates	quantum gates
circuits	**circuits**	**quantum circuit structure**

Key features: Higher-order operations

2) Quantum higher-order operations go beyond the quantum circuit model

CLASSICAL	QUANTUM	HIGHER-ORDER QUANTUM
data (bits) gates circuits	quantum data (qbits) quantum gates **circuits**	quantum data (qbits) quantum gates **quantum circuit structure**



Research goals

Quantum Technologies: Quantum circuit optimization

Optimization is a central challenge of current technologies, readily-available quantum hardware is limited

- Develop toolbox for quantum circuit/network optimization
- Identify fundamental circuit building blocks and construct optimal protocols for information processing

Quantum Foundations: Quantum computing with indefinite causal order

Quantum theory may allow us to go beyond the quantum circuit model into more powerful models of computation

- Uncover the power and cost of computations with indefinite causal order
- Investigate higher-order quantum computing as potential new computational model

Application: Channel Discrimination

→ Identification of circuit elements

→ Generalized hypothesis testing

INPUT: k calls / queries of

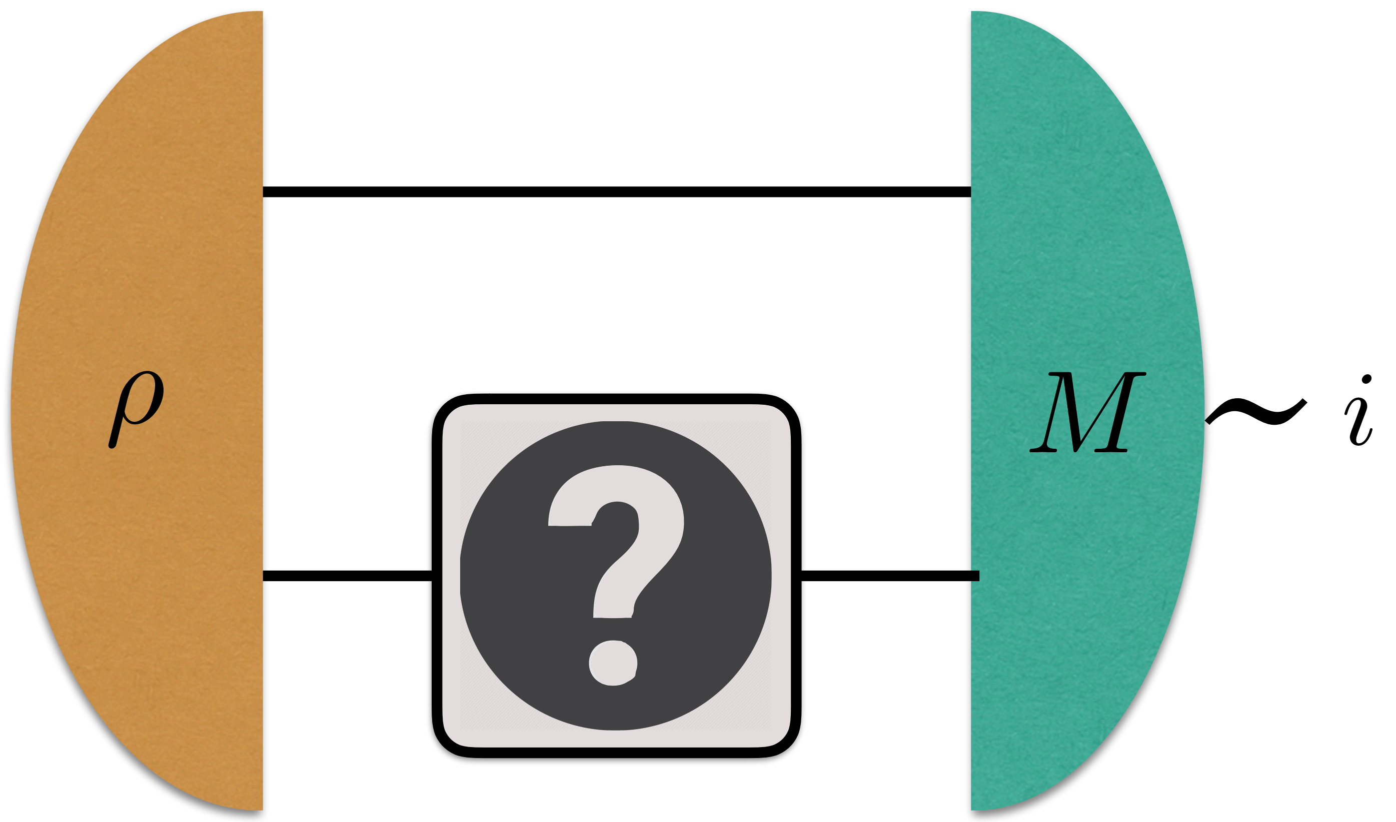
PROMISE: $\in \left\{ \underset{p_1}{\widetilde{C}_1}, \underset{p_2}{\widetilde{C}_2}, \underset{p_3}{\widetilde{C}_3} \right\}$

TASK: guess which channel is.

Application: Channel Discrimination

Standard approach

strategy as state and measurement



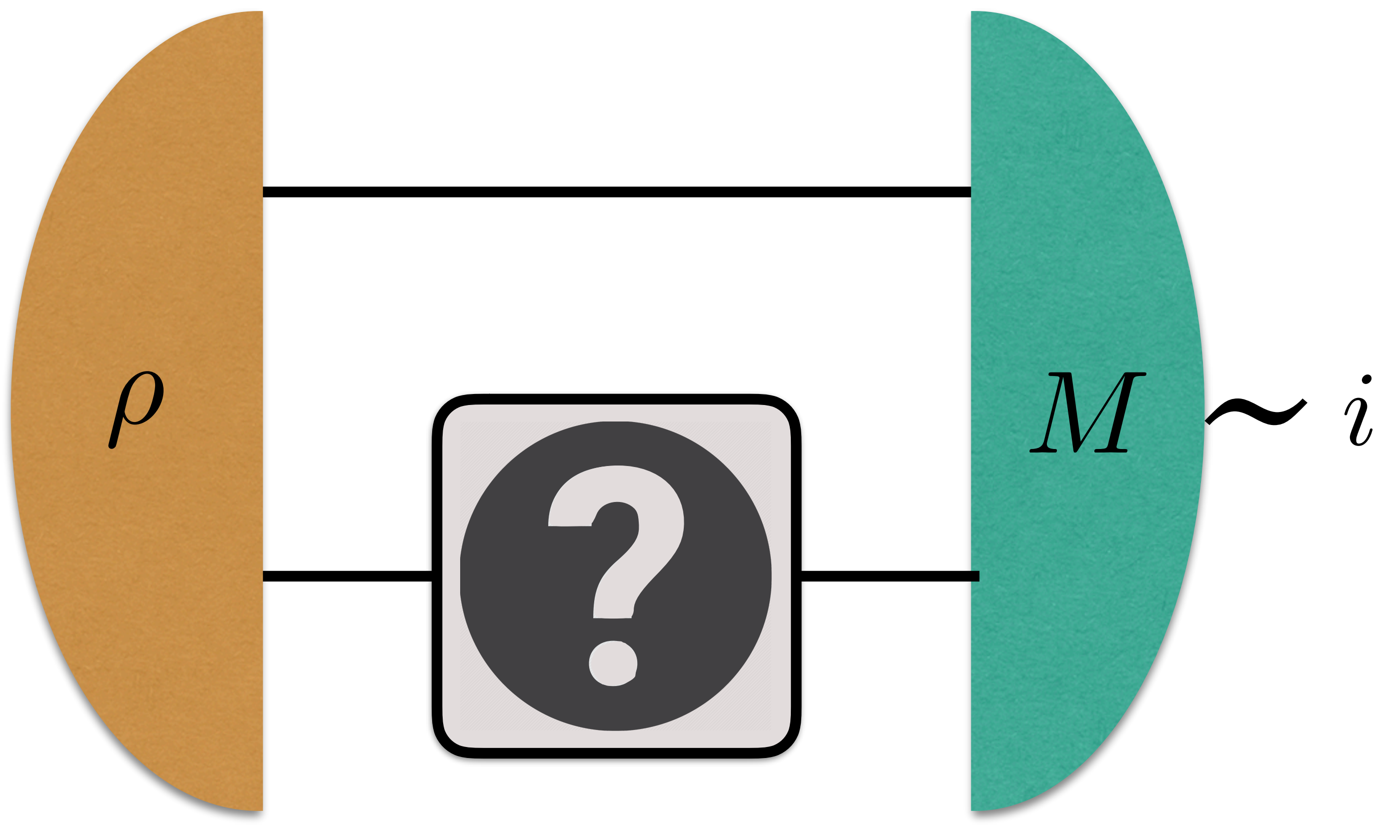
$$P = \max_{\rho, \{M_i\}} \sum_i \mathrm{tr}(\widetilde{C}_i \otimes \widetilde{\mathbb{I}}[\rho] M_i)$$
$$\text{s.t.} \quad M_i \geq 0 \ \forall i, \ \sum_i M_i = \mathbb{I}$$
$$\rho \geq 0, \ \mathrm{tr}(\rho) = 1$$

Nonlinear

Application: Channel Discrimination

Standard approach

strategy as state and measurement



$$P = \max_{\rho,\{M_i\}} \sum_i \mathrm{tr}(\widetilde{C}_i \otimes \widetilde{\mathbb{I}}[\rho] M_i)$$

$$\text{s.t.} \quad M_i \geq 0 \; \forall i, \; \sum_i M_i = \mathbb{I}$$

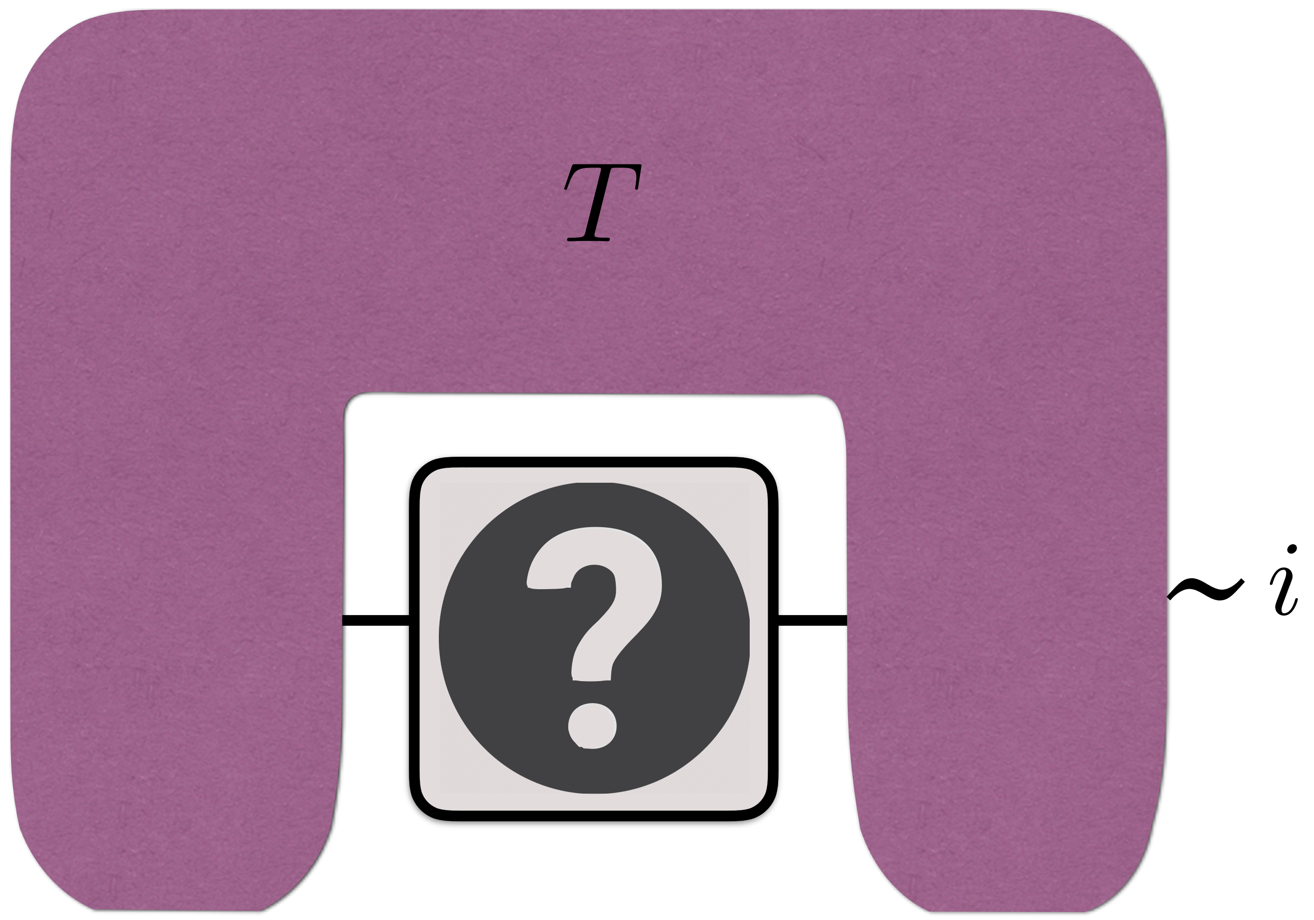
$$\rho \geq 0, \; \mathrm{tr}(\rho) = 1$$

Nonlinear

$\Longleftrightarrow$

Higher-order approach

strategy as probabilistic higher-order operation



$$P = \max_{\{T_i\}} \sum_i \mathrm{tr}(C_i T_i)$$

$$\text{s.t.} \quad T_i \geq 0 \; \forall i, \; \sum_i T_i = \sigma \otimes \mathbb{I}$$

$$\mathrm{tr}(\sigma) = 1$$

Semidefinite Programming (SDP)

My Highlight Result: Channel Discrimination

Multiple queries of the unknown operation

[BQM21] **Strict hierarchy between parallel, sequential, indefinite-causal-order strategies for channel discrimination**, **Physical Review Letters** 127, 200504 (2021)

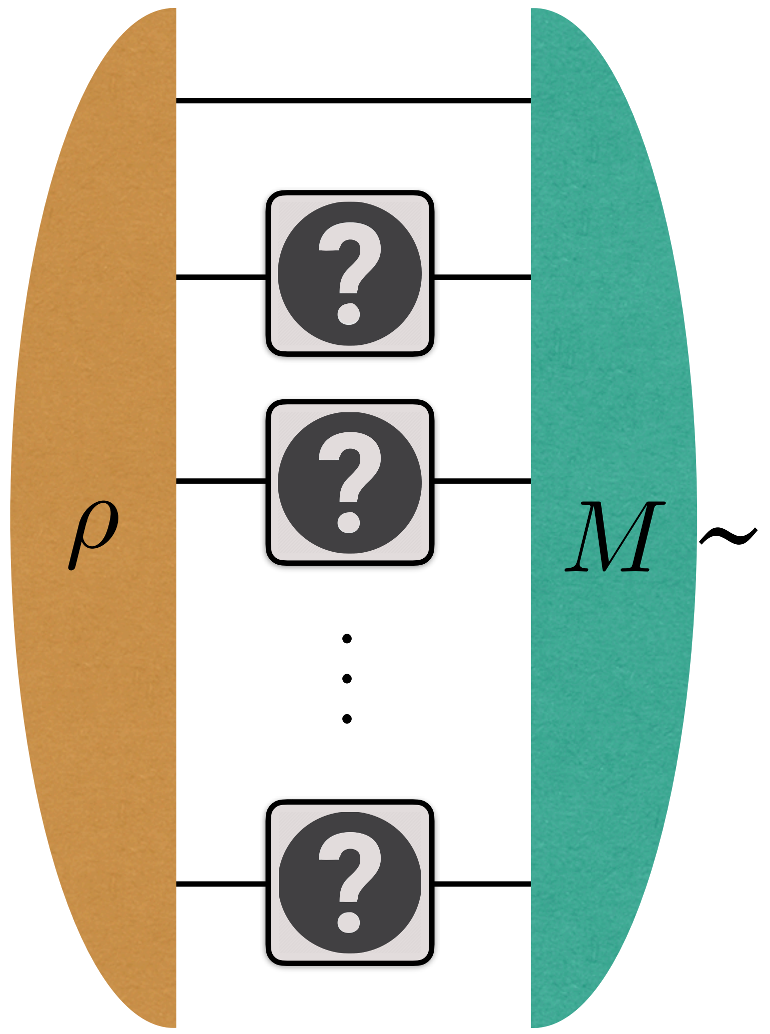
[BQM22] **Unitary channel discrimination beyond group structures: Advantages of sequential and indefinite-causal-order strategies**, **Journal of Mathematical Physics** 63, 042203 (2022)

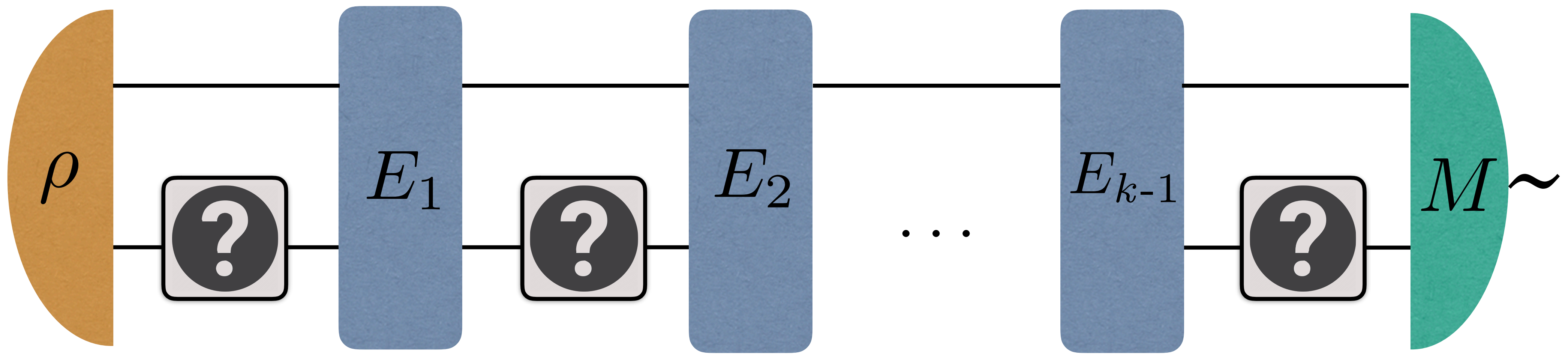
My Highlight Result: Channel Discrimination

Multiple queries of the unknown operation

PARALLEL

SEQUENTIAL





$$P^{\mathrm{PAR}} \leq P^{\mathrm{SEQ}}$$

PREVIOUSLY

question: is there a strict separation?

difficulty: upper bounds for parallel case

evidence: no gap for several cases ('01,'08)

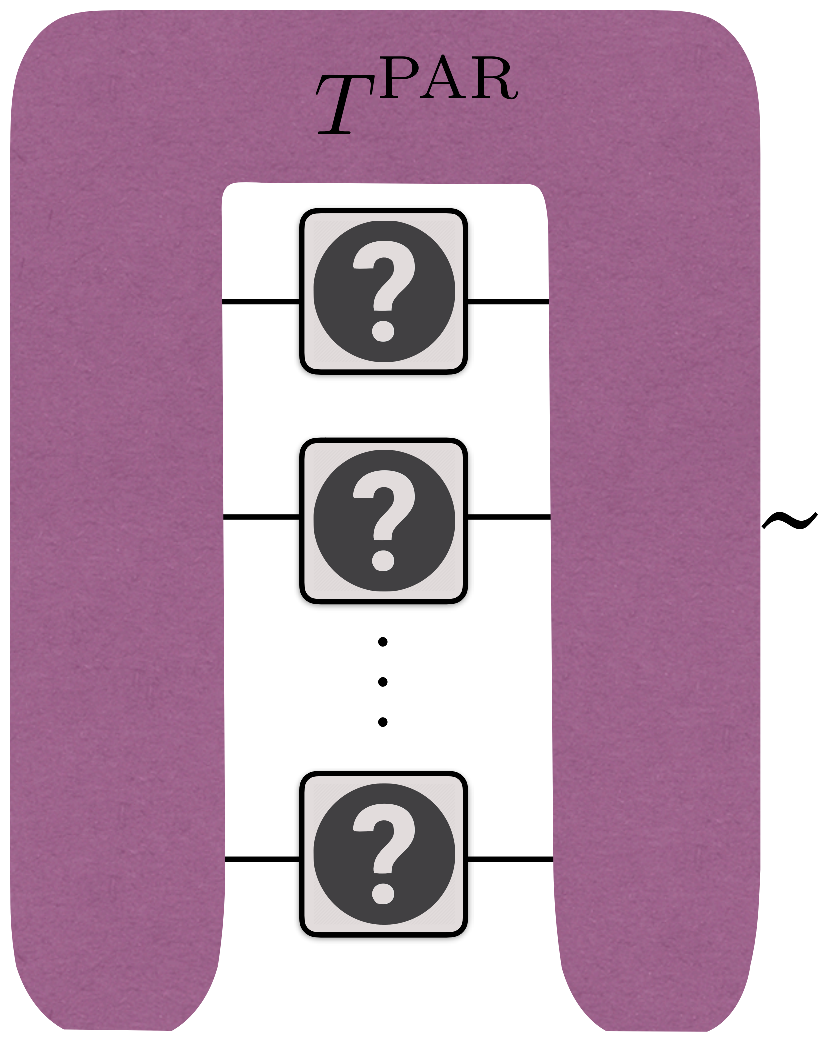
partial result: one example, particular channels ('10)

[1] Aharanov, Kitaev, Nisan, STOC (1997)

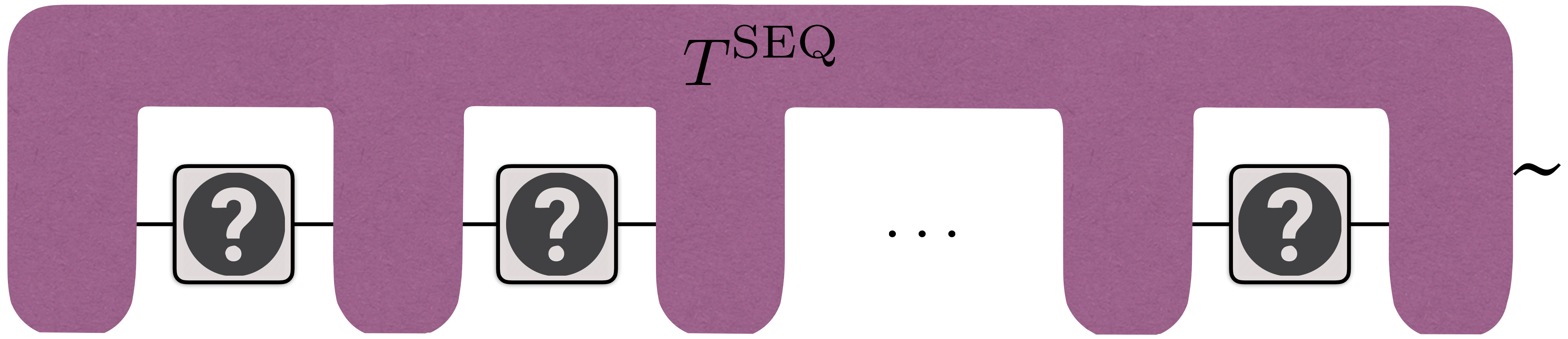
My Highlight Result: Channel Discrimination

Multiple queries of the unknown operation

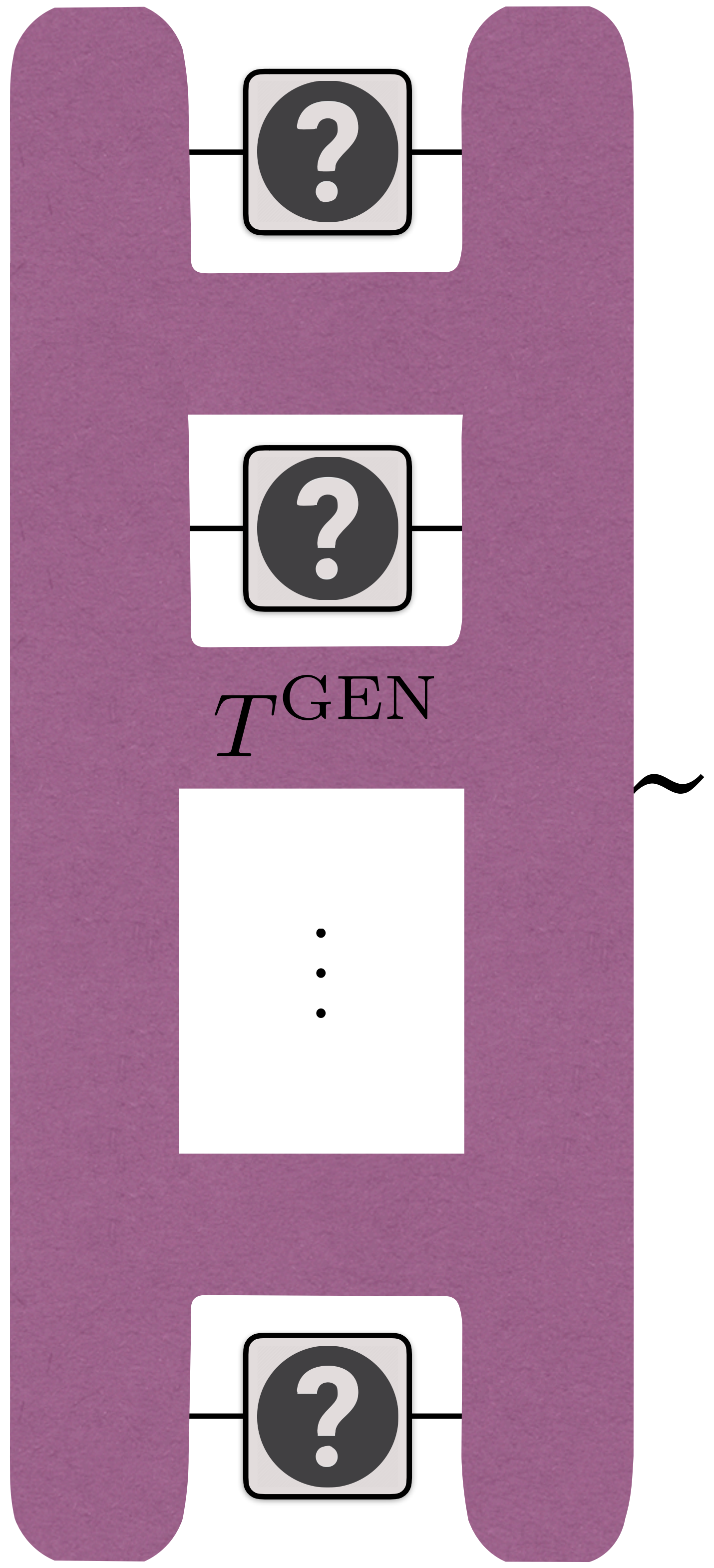
PARALLEL



SEQUENTIAL



GENERAL



$$P^{\text{PAR}} \leq P^{\text{SEQ}} \leq P^{\text{GEN}}$$

Insight: solve problem with higher-order operations

My Highlight Result: Channel Discrimination

- Maximum probability of success under each class of strategy

$$P^{\mathrm{PAR}} < P^{\mathrm{SEQ}}$$

Strict hierarchy between discrimination strategies
for the probability of success

[BQM21] **Physical Review Letters** (2021)
[BQM22] **Journal of Mathematical Physics** (2022)

My Highlight Result: Channel Discrimination

- Maximum probability of success under each class of strategy

$$P^{\mathrm{PAR}} < P^{\mathrm{SEQ}} < P^{\mathrm{GEN}}$$

Strict hierarchy between discrimination strategies
for the probability of success

[BQM21] Physical Review Letters (2021)
[BQM22] Journal of Mathematical Physics (2022)

My Highlight Result: Channel Discrimination

- Maximum probability of success under each class of strategy

$$P^{\text{PAR}} < P^{\text{SEQ}} < P^{\text{GEN}} \leq \mathcal{B}(d, k, N)$$

Upper bound for the probability of success
of discriminating unitary operations

[BQM21] Physical Review Letters (2021)
[BQM22] Journal of Mathematical Physics (2022)

My Highlight Result: Channel Discrimination

- Maximum probability of success under each class of strategy

$$P^{\text{PAR}} = P^{\text{SEQ}} = P^{\text{GEN}} = \mathcal{B}(d, k, N)$$

Optimal: achieved by some sets of
highly-symmetric unitary operations

[BQM21] Physical Review Letters (2021)
[BQM22] Journal of Mathematical Physics (2022)

My Highlight Result: Channel Discrimination

- Maximum probability of success under each class of strategy

$$\underbrace{P^{\mathrm{PAR}} < P^{\mathrm{SEQ}} < P^{\mathrm{GEN}}}_{\text{Rigorous method of computer-assisted proofs}} \underbrace{\leq \mathcal{B}(d,k,N)}_{\text{Analytical upper bound from dual formulation of SDPs}}$$

Rigorous method of computer-assisted proofs

Analytical upper bound from dual formulation of SDPs

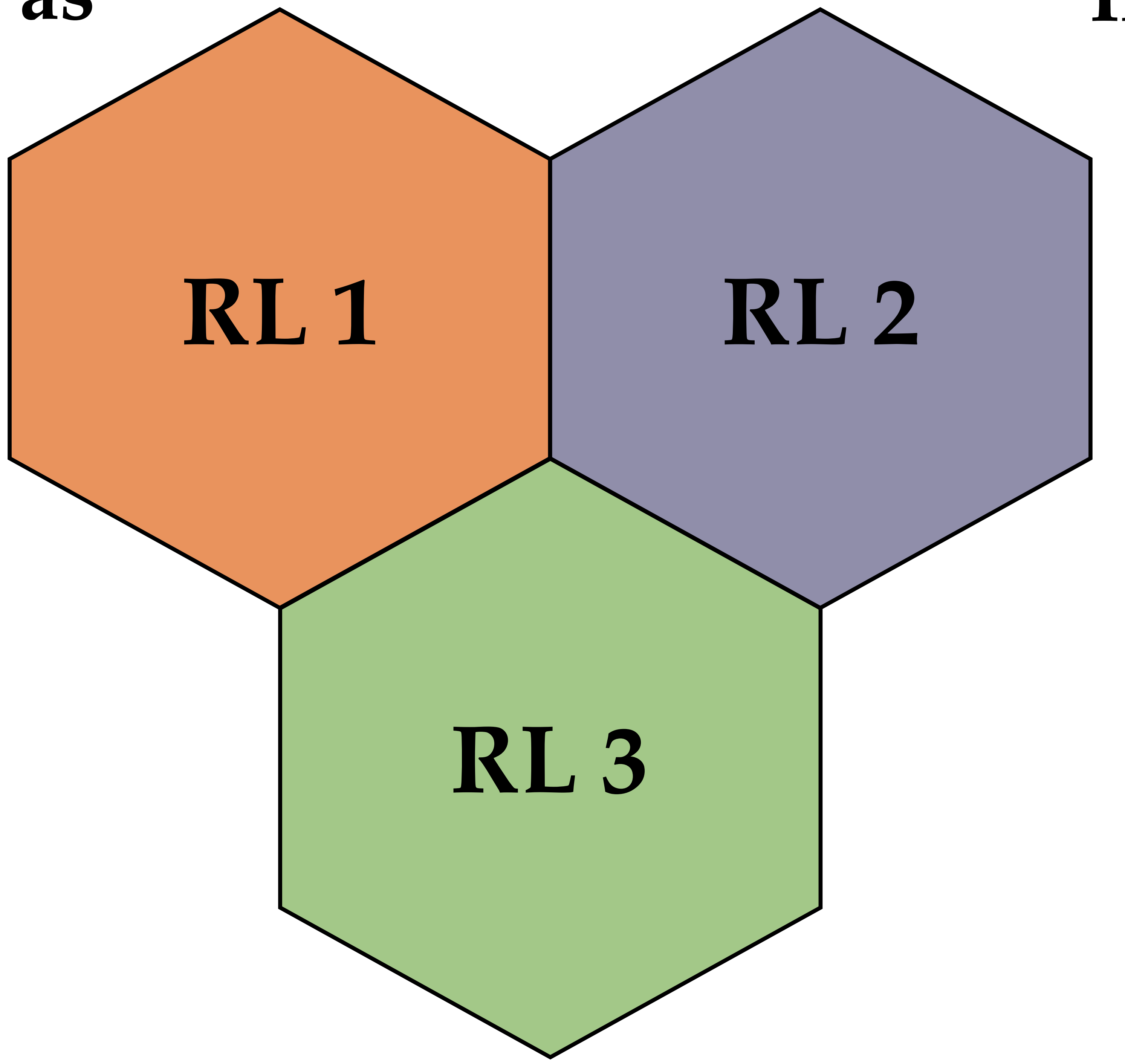
github.com/jessicabavaresco

$\Longrightarrow$ **Solved decades-long open problem** and **introduced new techniques to the field**

Research Plan

Quantum circuits as higher-order operations

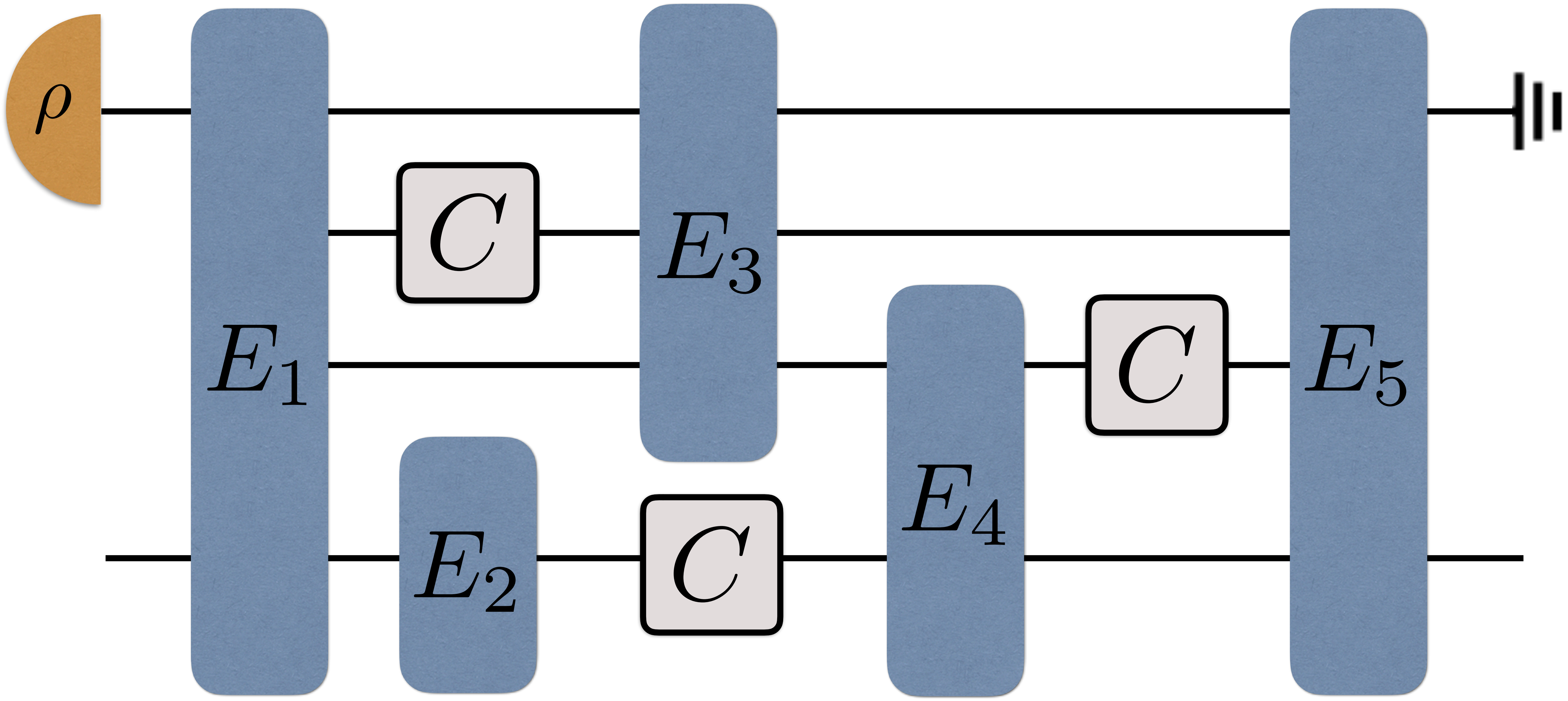
Indefinite causal order as a computational resource



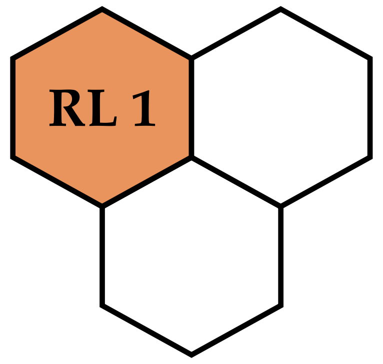
Quantum correlations and certification of nonclassical resources

Research Line 1

Quantum circuits as higher-order operations



$$\overset{?}{\mapsto} \quad f(\boxed{C})$$

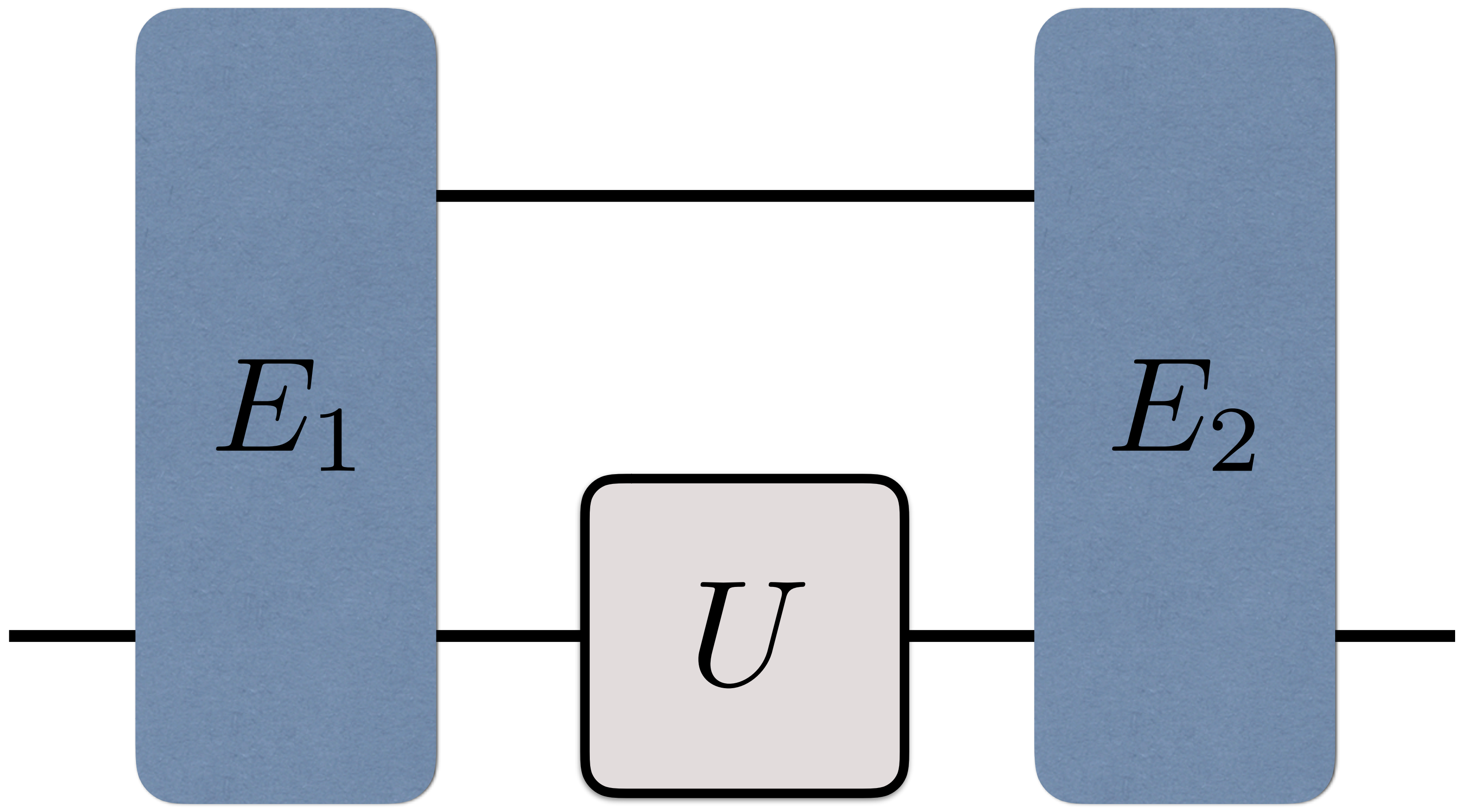


Research Line 1

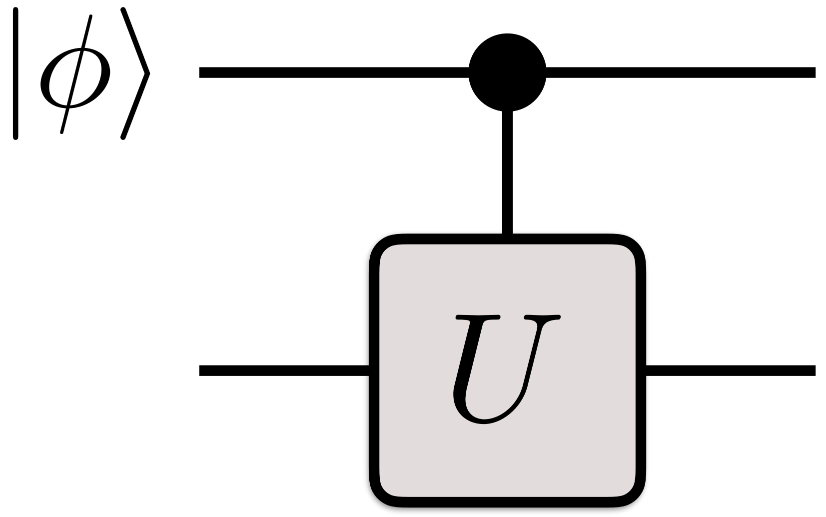
Quantum circuits as higher-order operations

“quantum `if` statement”

$$\begin{pmatrix} \texttt{if } |\phi\rangle \\ \texttt{then } U \end{pmatrix}$$



$\stackrel{?}{=}$



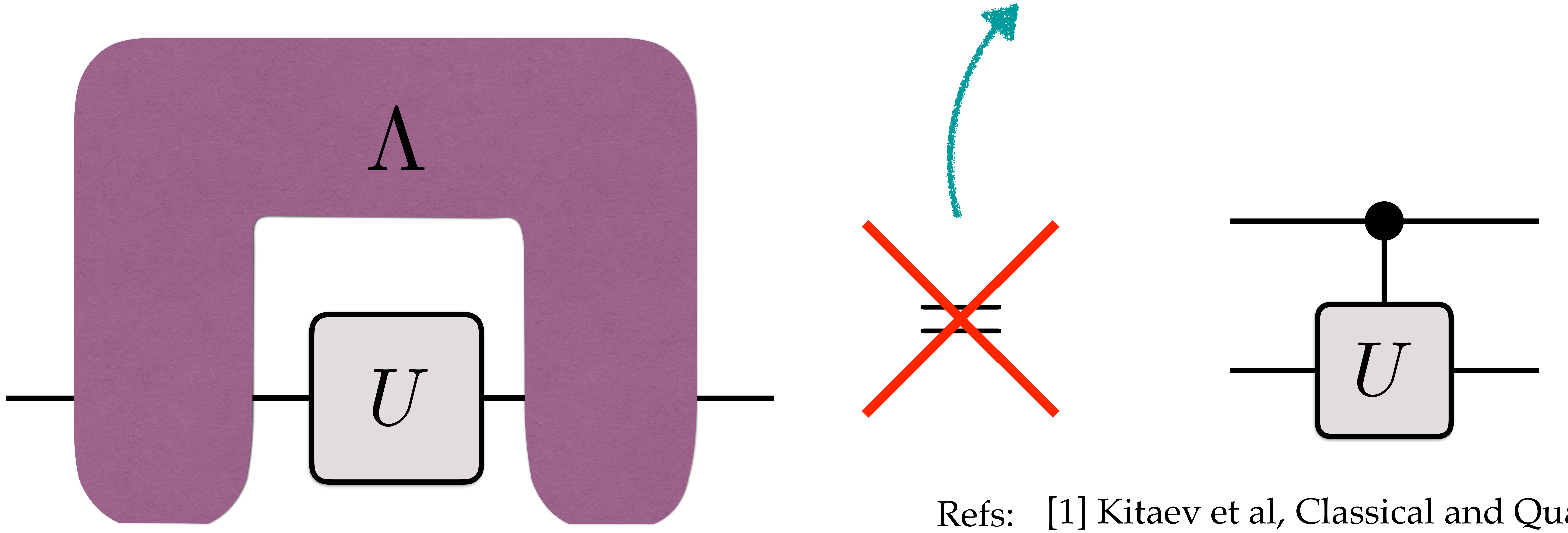
$\forall\ U$ unitary operations

RL 1

Quantum circuits as higher-order operations

no-go theorem for quantum data:
no cloning (no copying)

no-go theorem for quantum functions:
no controlization (no conditioning)



Refs: [1] Kitaev et al, Classical and Quantum Computation (2002)
[2] A. Soeda, ICQIT2013 (2013)
[3] Araújo et al, New J. Phys. 16 093026 (2014)
[4] Gavoróva et al, Phys. Rev. A 109, 032625 (2024)

Quantum circuits as higher-order operations

what are the **fundamental components** of a quantum computation and which elements can be obtained from transformations of others?

Research Line 1

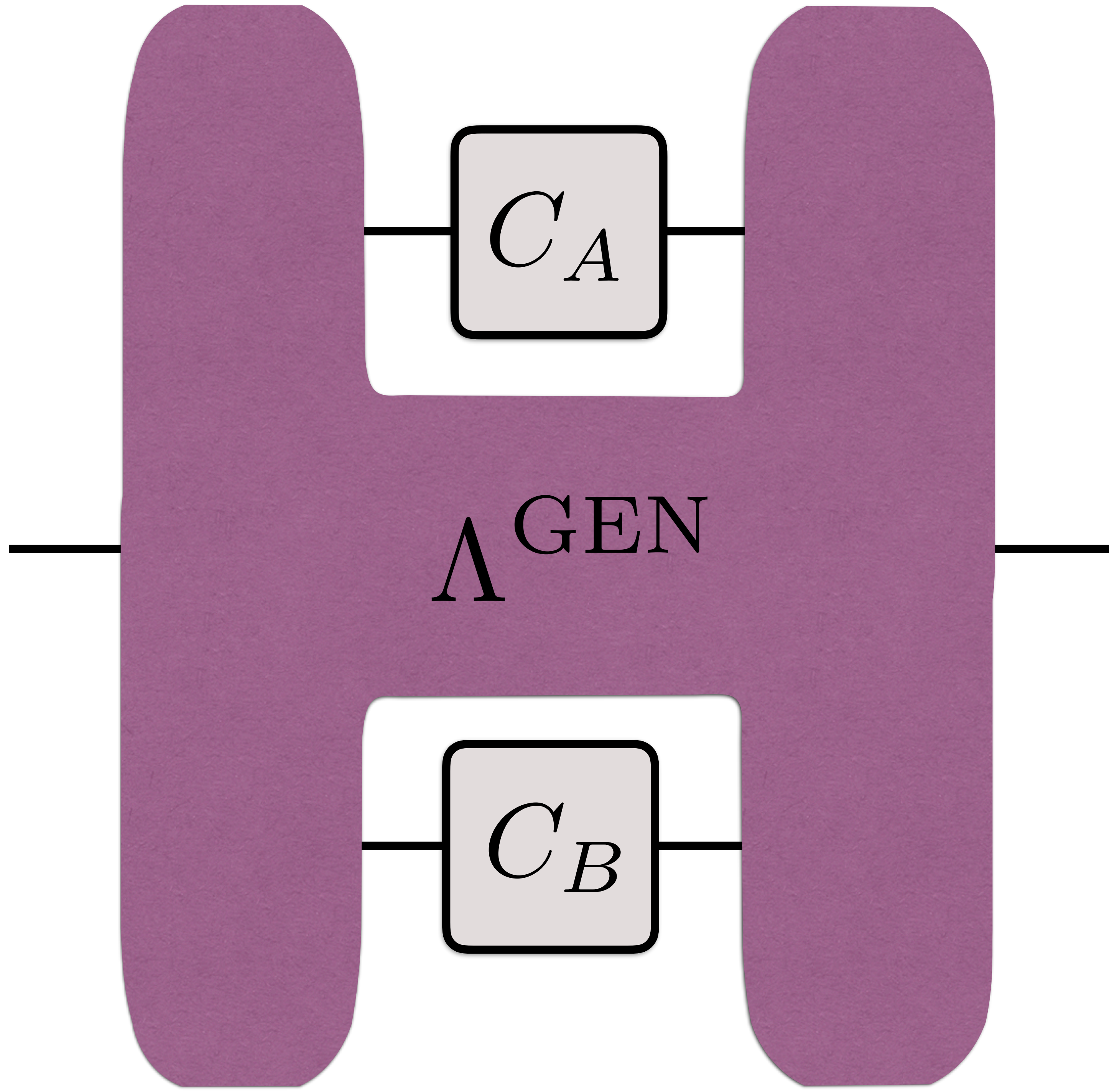
Quantum circuits as higher-order operations

what are the **fundamental components** of a quantum computation and which elements can be obtained from transformations of others?

what are the **optimal** protocols (quantum circuits) for these transformations and the required number of calls?

universal
deterministic / probabilistic
exact / approximate

Indefinite causal order as a computational resource

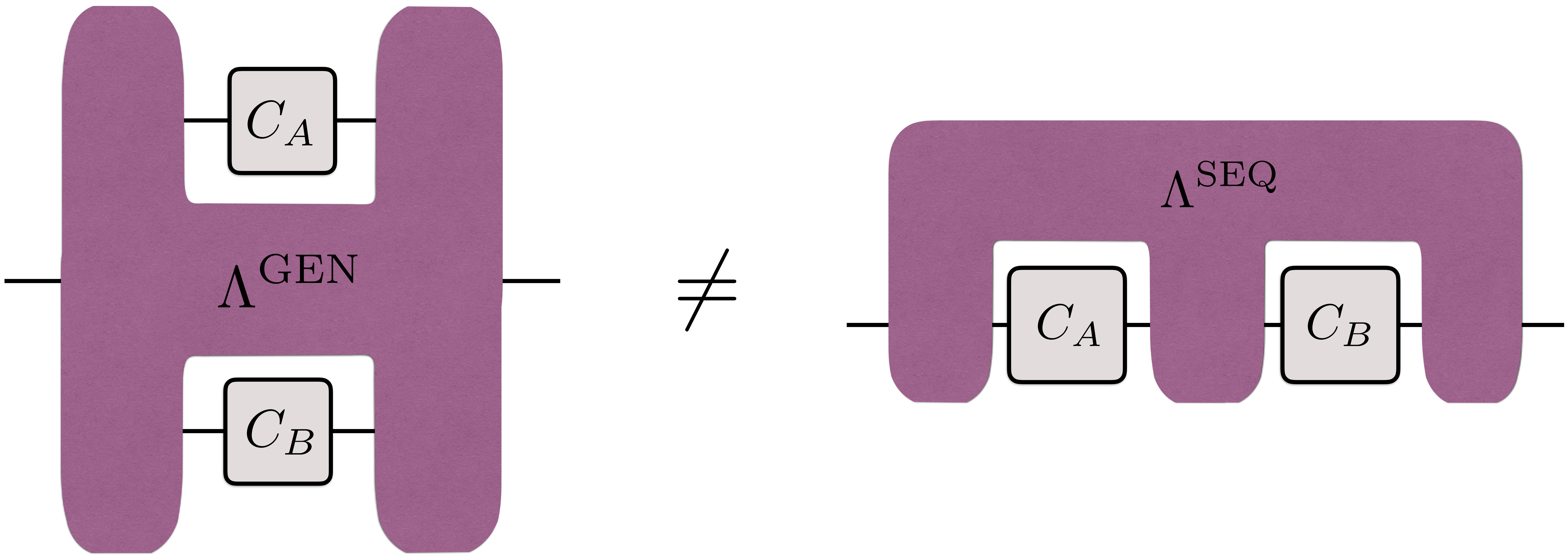


INDEFINITE CAUSAL ORDER

Known advantages:

- quantum query complexity
- communication complexity
- estimation precision
- channel discrimination
- …

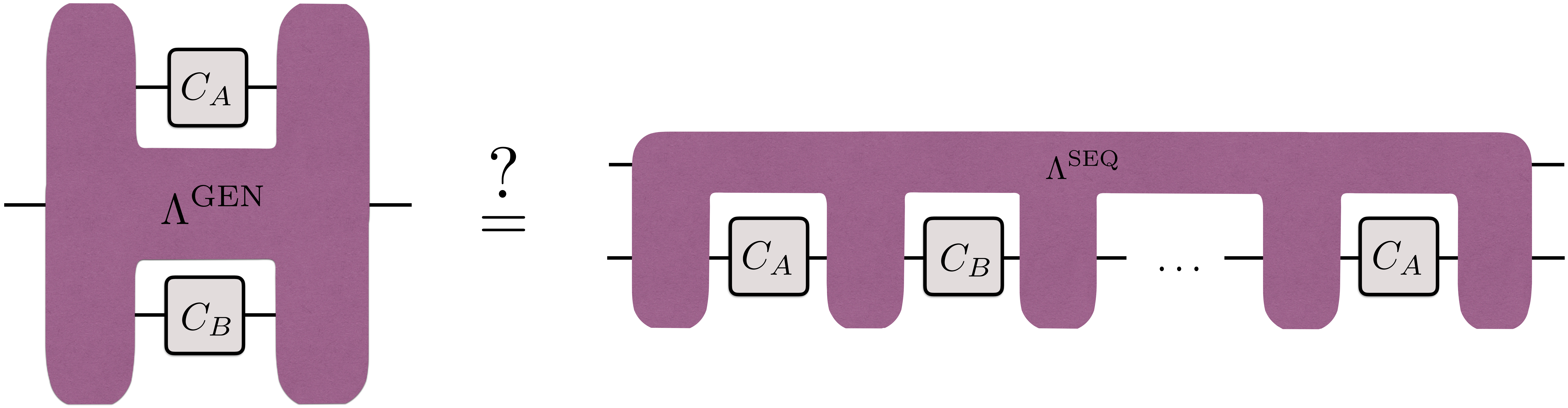
Indefinite causal order as a computational resource



RL 2

Research Line 2

Indefinite causal order as a computational resource



$\forall\, C_A, C_B$ general operations

RL 2

Indefinite causal order as a computational resource

what is the **cost of simulating** computations with indefinite causal order using standard quantum circuits?

RL 2

Research Line 2

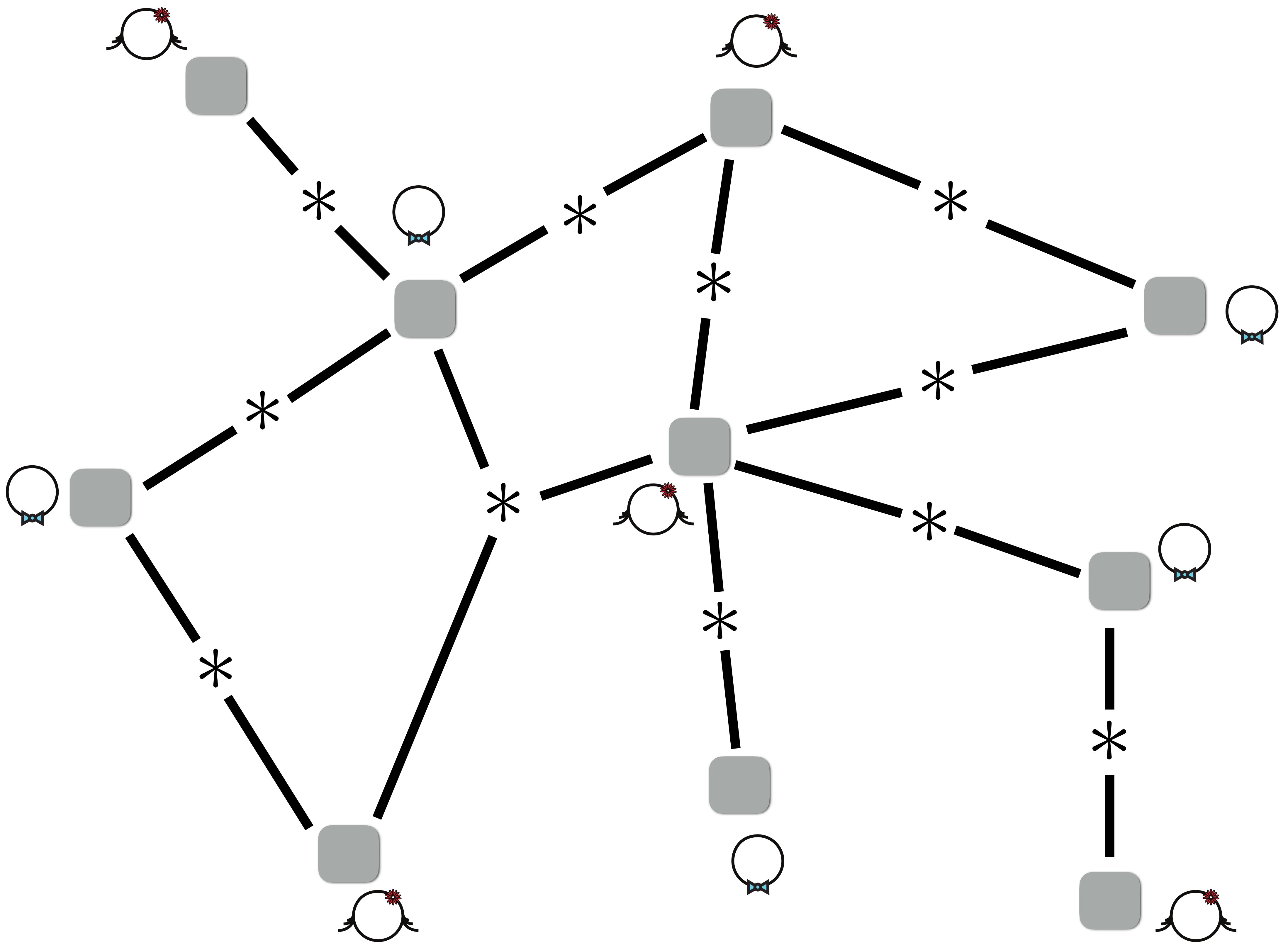
Indefinite causal order as a computational resource

what is the **cost of simulating** computations with indefinite causal order using standard quantum circuits?

could indefinite causal order lead the a **new paradigm of quantum computation**?

RL 2

Quantum correlations and certification of nonclassical resources



$$\{p(a_1, a_2, \ldots, a_N | x_1, x_2, \ldots, x_N)\}$$

classical?
quantum?

RL 3

Quantum correlations and certification of nonclassical resources

can **all quantum systems** lead to nonclassical correlations?

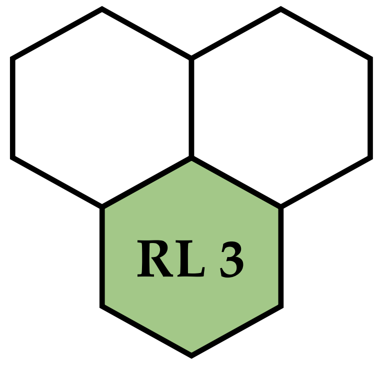
RL 3

Research Line 3

Quantum correlations and certification of nonclassical resources

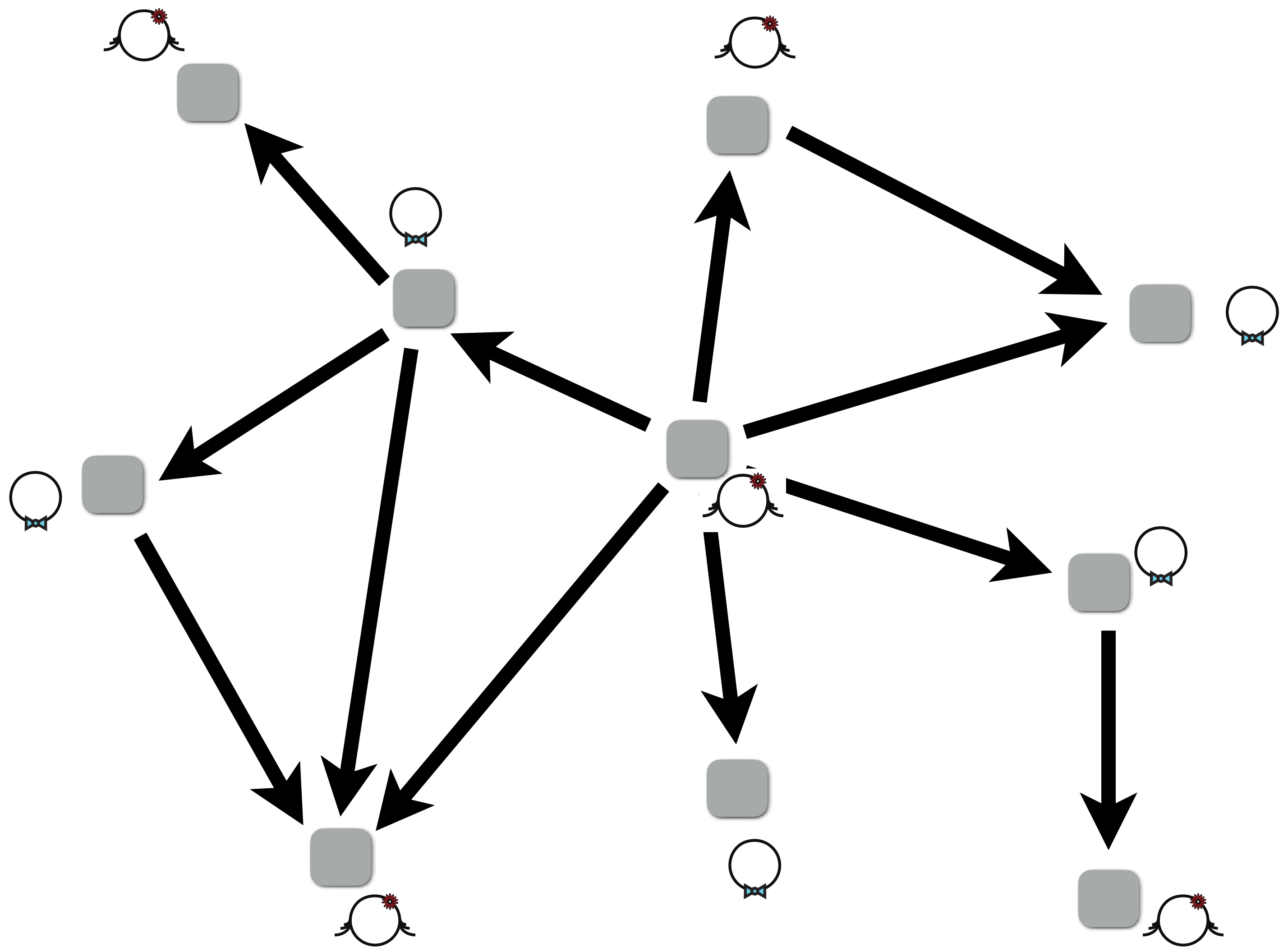
can **all quantum systems** lead to nonclassical correlations?

can we find optimal **network protocols** for certifying nonclassical resources using higher-order operations?



Research Line 3

Quantum correlations and certification of nonclassical resources



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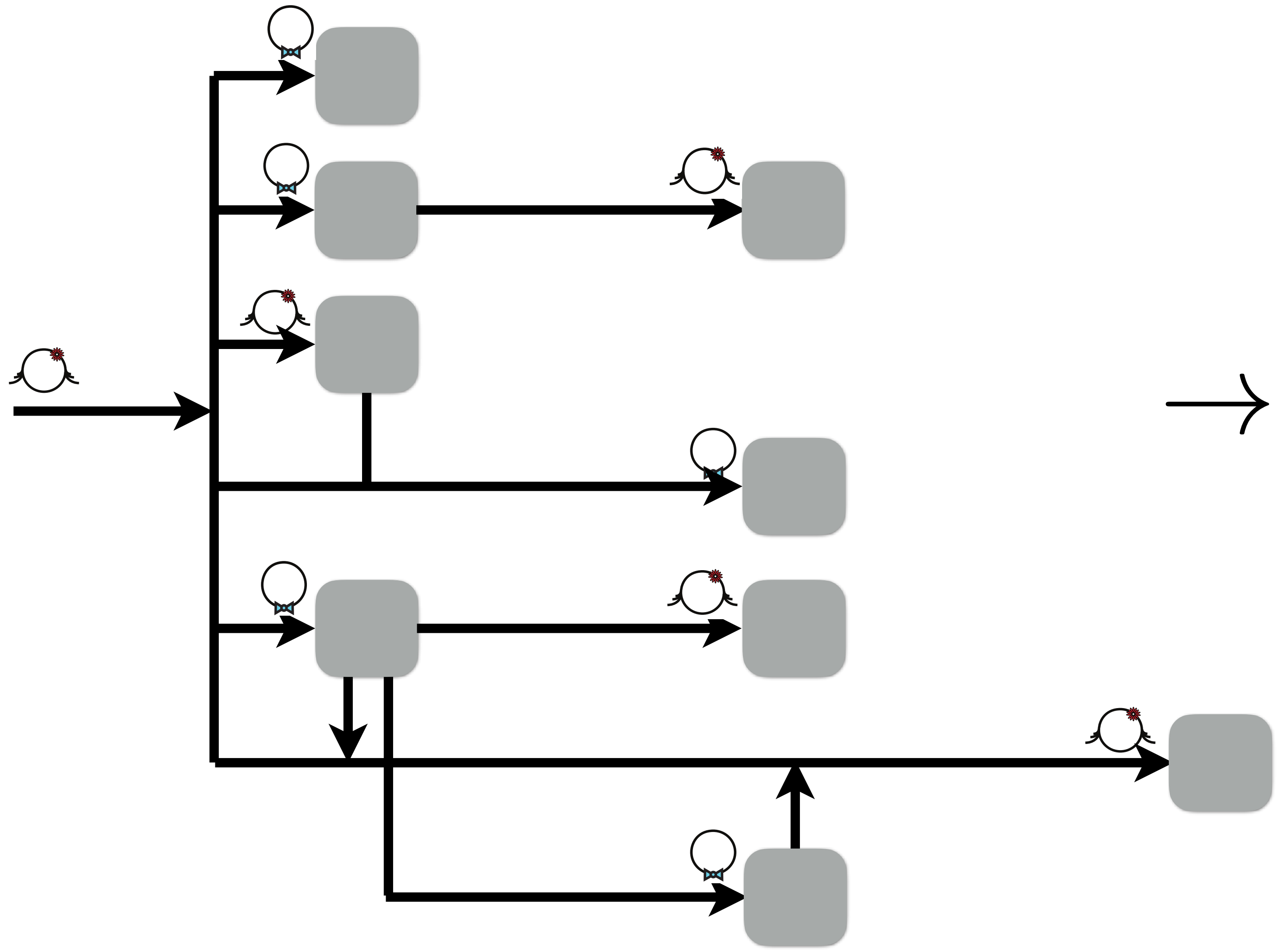

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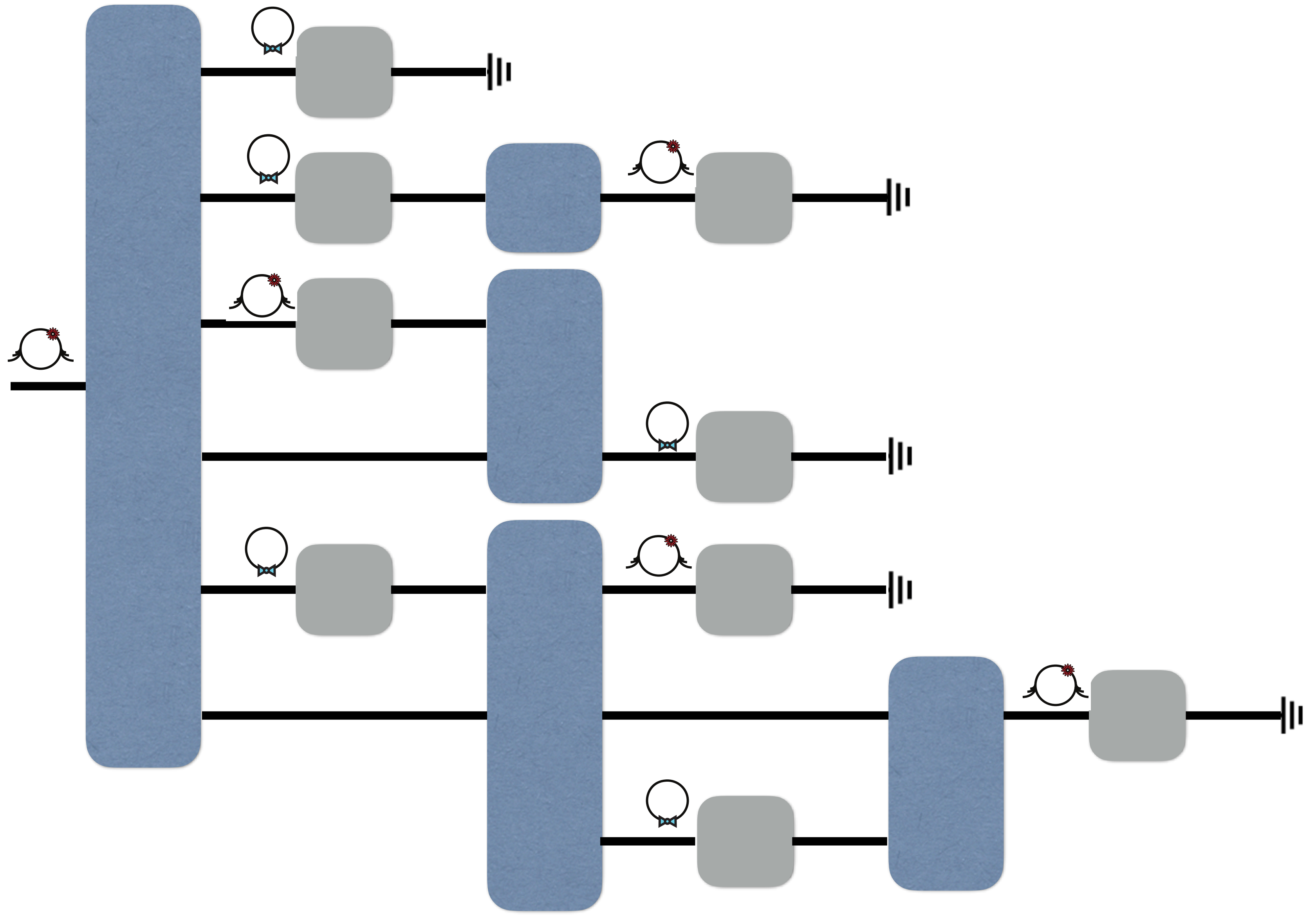
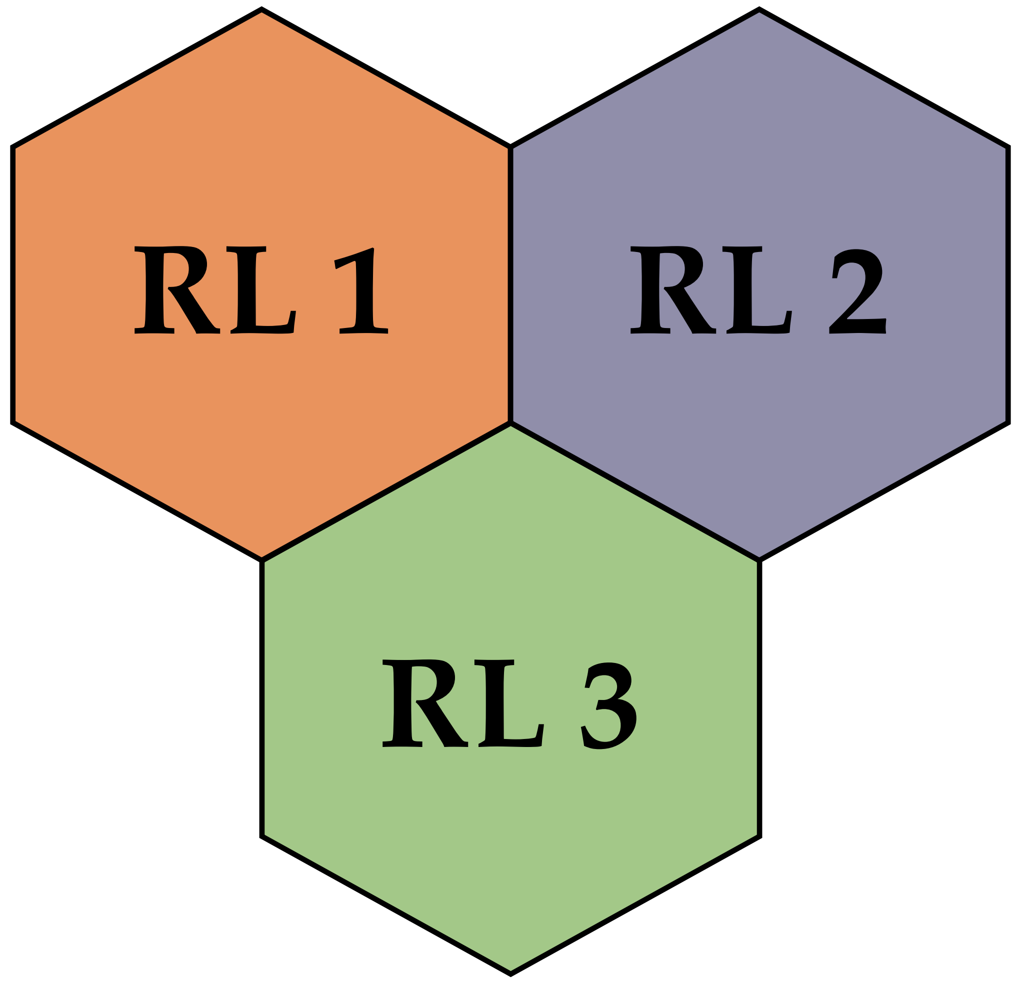


quantum networks as higher-order operations

RL 3

Overview



Quantum Technologies goal:
Toolbox for quantum circuit/ network optimization

Quantum Foundations goal:
Quantum computing with indefinite causal order

- Research project at the interface of **Computer Science and Quantum Information Science**.
- Timely problems with **applications** in both to foundations and technologies.

Integration

LIP6

IRIF — INSTITUT DE RECHERCHE EN INFORMATIQUE FONDAMENTALE

LMF — Laboratoire Méthodes Formelles

QI team: Eleni Diamanti, Alex Grilo, Frédéric Grosshans, Elham Kashefi, Damian Markham, Marco Túlio Quintino

- Quantum correlations, networks (D.M., F.G, M.T.Q, E.D.) 3
- Quantum complexity, verification (E.K., A.G.) 1 2
- Higher-order operations (E.K., M.T.Q.) 1 2

Algorithms and Complexity team: Sophie Laplante, Simon Apers, Frédéric Magniez

- Computational, communication, and query complexity (S.L., S.A.) 1 2
- Device-independent protocols (F.M.) 3
- Claudia Faggian (PPS): lambda calculus, linear logic 2

QuaCS team: Pablo Arrighi, Benoît Valiron, Marc de Visme

- New models for quantum computation (B.V., M.V.) 2
- Indefinite causal order (P.A., B.V.) 2
- Category theory (B.V., M.V.) 1 2

Broader French research ecosystem

Other potential collaborations in France:

Grenoble

- **Cyril Branciard:** higher-order operations, nonlocality (CNRS I. Néel)
- **Alastair Abbott:** indefinite causal order (Inria QINFO)
- **Andreas Bluhm:** quantum measurement simulation (CNRS LIG)

Toulouse

- **Ion Nechita:** joint measurability (CNRS LPT)

Saclay

- **Marc-Olivier Renou:** quantum networks (Inria)
- **Titouan Carette:** categorical methods for higher-order (Inria)

Paris region:

Integration and funding

Paris Centre for Quantum Technologies

QuanTiP

anr Jeunes Chercheuses et Jeunes Chercheurs (JCJC)

Potential industry partners

- Quandela (quantum computing)
- Pasqal (quantum computing)
- Alice & Bob (quantum computing)
- VeriQloud (quantum cryptography)
- Welinq (quantum communication and networks)

Network of collaborators

Switzerland
Nicolas Brunner (Geneva)
Ämin Baumeler (Zurich)
…

Italy
Costantino Budroni (Pisa)

Austria
Marcus Huber (Vienna)
Mohammad Mehboudi (Vienna)
…

Ireland
Simon Milz (Dublin)

UK
Paul Skrzypczyk (Bristol)

Japan
Mio Murao (Tokyo)
Satoshi Yoshida (Tokyo)
…

Canada
Hlér Kristjánsson (Waterloo)

Hong Kong
Giulio Chiribella

China
Huan Cao (Hefei)

PhD in June 2021

13 publications, 1 preprint
7 as first author
over 40 co-authors

2+1 invited conference talks
10+1 accepted conference talks
16+1 invited seminars

2 postdoc grants (MSCA and SNSF)
2 research grants
1 stipend
= ~630k EUR

Fonds national suisse

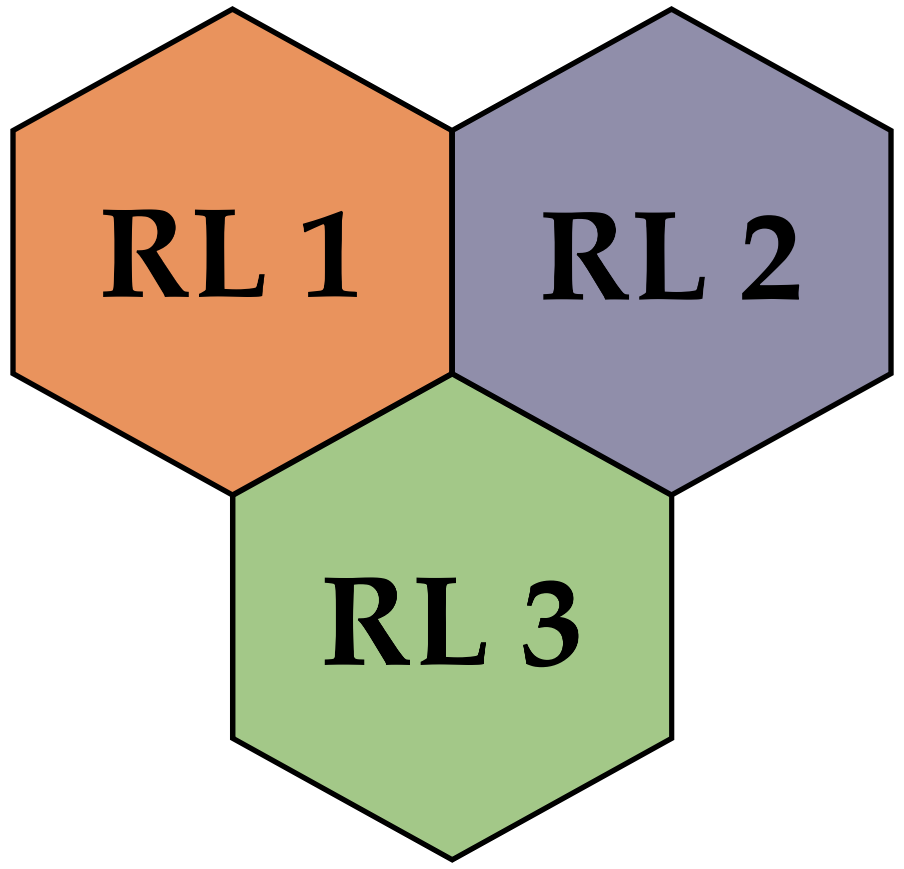
MARIE CURIE ACTIONS

1 conference steering committee
1 PhD thesis jury

$$P^{\mathrm{PAR}} < P^{\mathrm{SEQ}} < P^{\mathrm{GEN}}$$

Quantum circuits as higher-order operations

Indefinite causal order as a computational resource



Quantum correlations and certification of nonclassical resources

Thank you for your attention.

Extra

Channel Discrimination as SDP

$$P^{\mathcal{S}} = \max_{\{T_i^{\mathcal{S}}\}} \sum_i p_i \,\mathrm{Tr}\left(C_i^{\otimes 2}\, T_i^{\mathcal{S}}\right)$$

PRIMAL

given $\{p_i, C_i\}$

maximize $\sum_i p_i \mathrm{Tr}(T_i^{\mathcal{S}}\, C_i^{\otimes 2})$

subject to $T_i^{\mathcal{S}} \geq 0 \;\forall\, i, \quad \sum_i T_i^{\mathcal{S}} = W^{\mathcal{S}}$

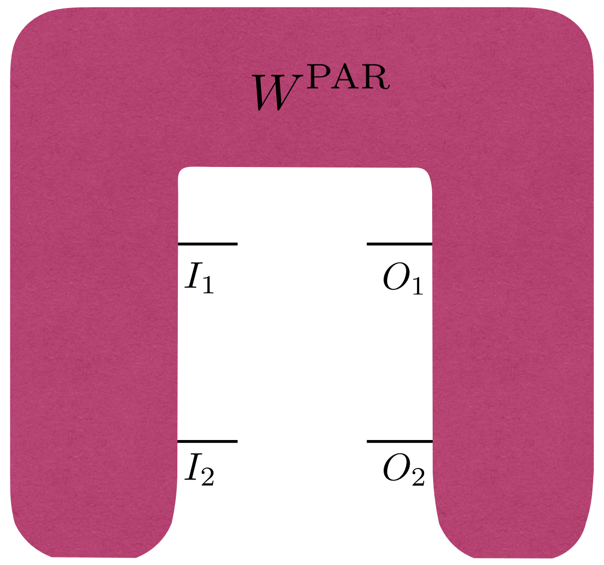
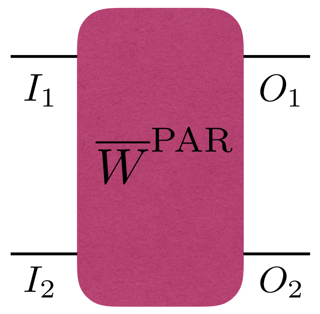
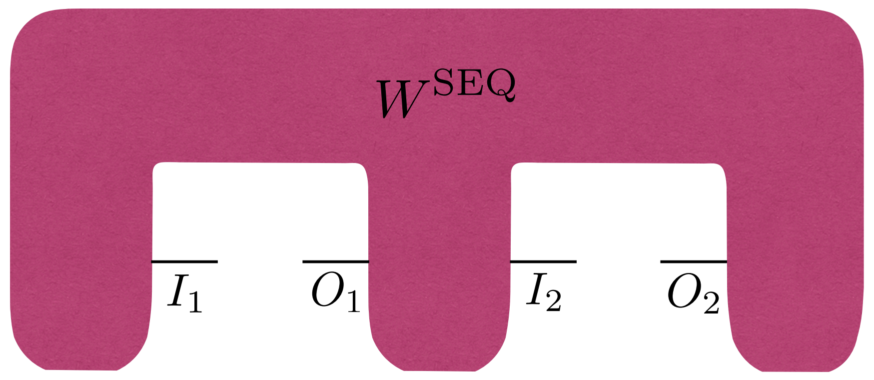
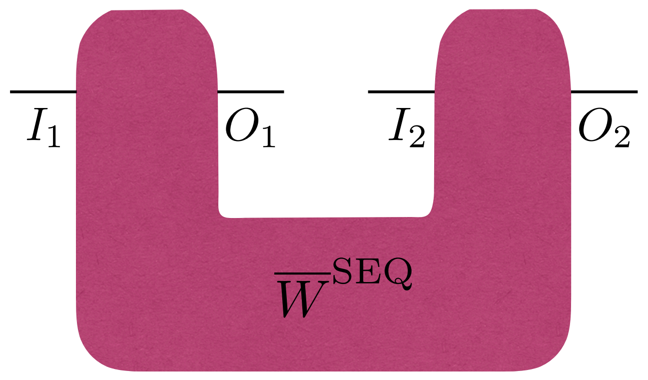
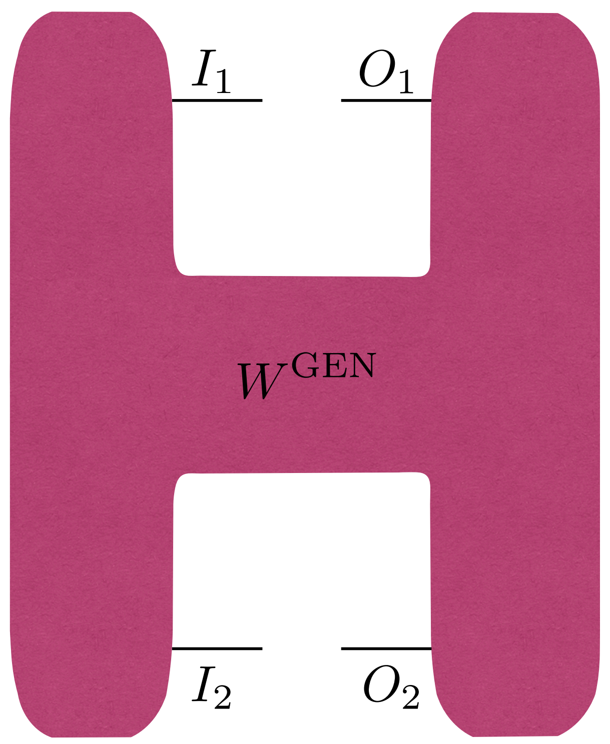
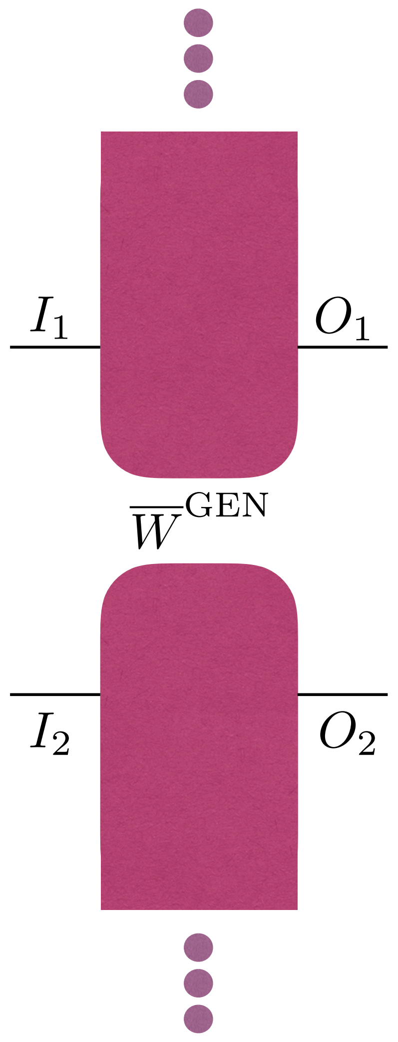
DUAL

given $\{p_i, C_i\}$

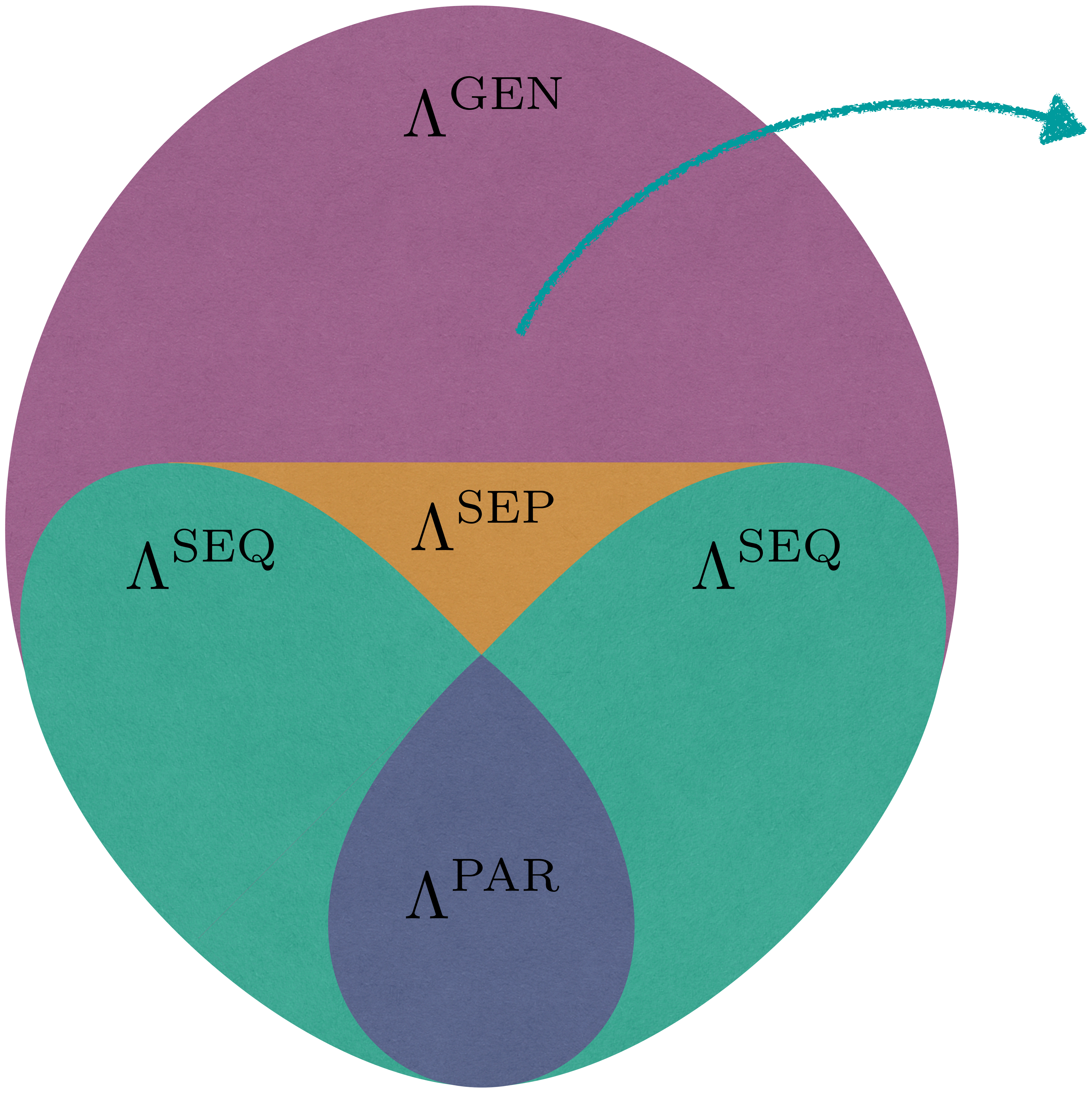
minimize λ

subject to $p_i\, C_i^{\otimes 2} \leq \lambda\, \overline{W}^{\mathcal{S}} \quad \forall\, i$

$$\mathrm{Tr}(W\,\overline{W}) = 1 \quad \forall \;\; W \in \mathcal{W},\; \overline{W} \in \overline{\mathcal{W}}$$

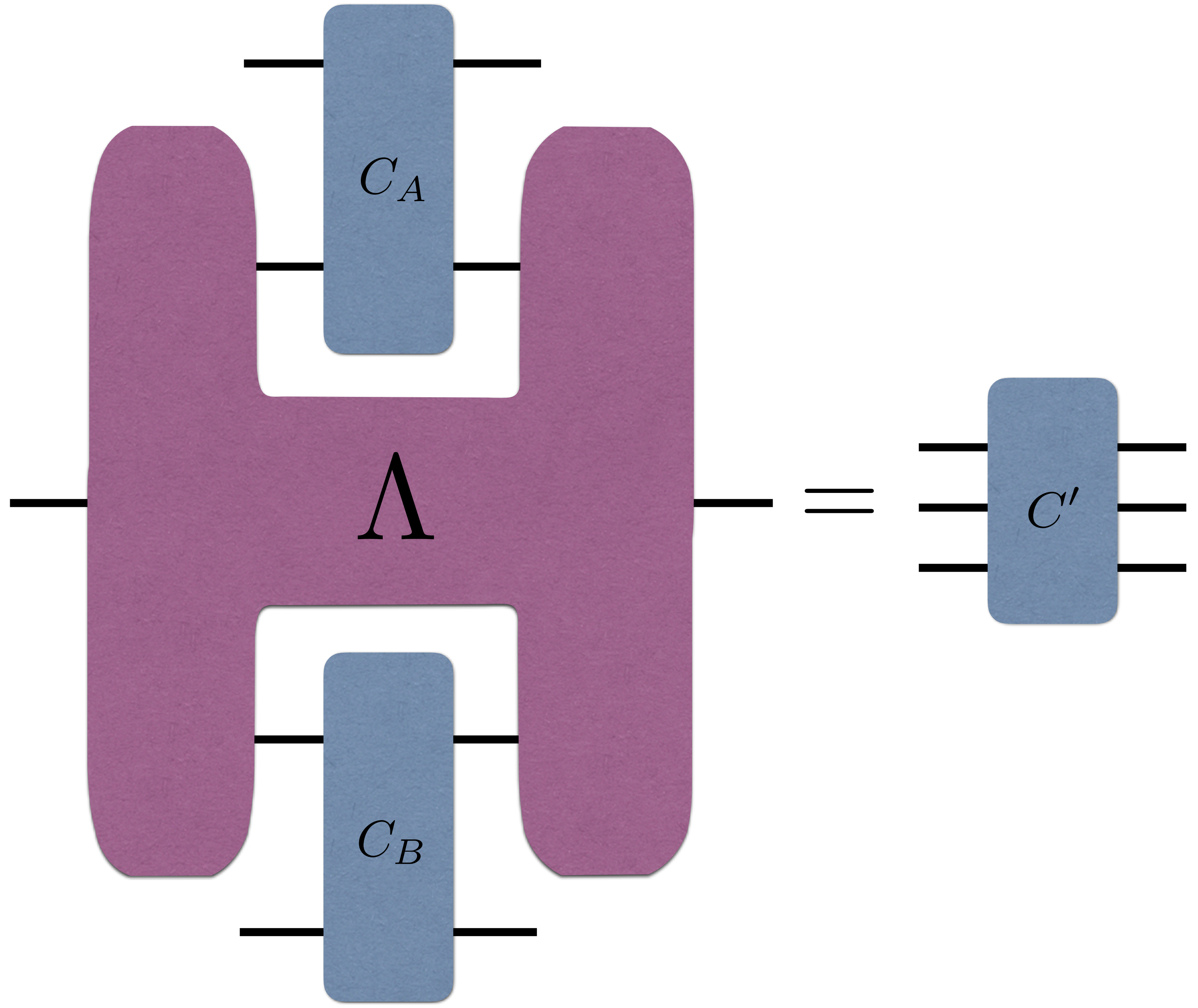
<table>
<tr><th></th><th colspan="2">PROCESS</th><th colspan="2">DUAL AFFINE (CHANNEL)</th></tr>
<tr><td>PARALLEL</td><td>
</td><td>$\mathrm{Tr}(W^{\mathrm{PAR}}) = d_{O_1}d_{O_2}$
$W^{\mathrm{PAR}} = {}_{O_1O_2}W^{\mathrm{PAR}}$</td><td>
</td><td>$\mathrm{Tr}(\overline{W}^{\mathrm{PAR}}) = d_{I_1}d_{I_2}$
${}_{O_1O_2}\overline{W}^{\mathrm{PAR}} = {}_{I_1O_1I_2O_2}\overline{W}^{\mathrm{PAR}}$</td></tr>
<tr><td>SEQUENTIAL</td><td>
</td><td>$\mathrm{Tr}(W^{\mathrm{SEQ}}) = d_{O_1}d_{O_2}$
$W^{\mathrm{SEQ}} = {}_{O_2}W^{\mathrm{SEQ}}$
${}_{I_2O_2}W^{\mathrm{SEQ}} = {}_{O_1I_2O_2}W^{\mathrm{SEQ}}$</td><td>
</td><td>$\mathrm{Tr}(\overline{W}^{\mathrm{SEQ}}) = d_{I_1}d_{I_2}$
${}_{O_2}\overline{W}^{\mathrm{SEQ}} = {}_{I_2O_2}\overline{W}^{\mathrm{SEQ}}$
${}_{O_1I_2O_2}\overline{W}^{\mathrm{SEQ}} = {}_{I_1O_1I_2O_2}\overline{W}^{\mathrm{SEQ}}$</td></tr>
<tr><td>GENERAL</td><td>
</td><td>$\mathrm{Tr}(W^{\mathrm{GEN}}) = d_{O_1}d_{O_2}$
${}_{I_1O_1}W^{\mathrm{GEN}} = {}_{I_1O_1O_2}W^{\mathrm{GEN}}$
${}_{I_2O_2}W^{\mathrm{GEN}} = {}_{O_1I_2O_2}W^{\mathrm{GEN}}$
$W^{\mathrm{GEN}} = {}_{O_1}W^{\mathrm{GEN}} + {}_{O_2}W^{\mathrm{GEN}} - {}_{O_1O_2}W^{\mathrm{GEN}}$</td><td>
</td><td>$\mathrm{Tr}(\overline{W}^{\mathrm{GEN}}) = d_{I_1}d_{I_2}$
${}_{O_1}\overline{W}^{\mathrm{GEN}} = {}_{I_1O_1}\overline{W}^{\mathrm{GEN}}$
${}_{O_2}\overline{W}^{\mathrm{GEN}} = {}_{I_2O_2}\overline{W}^{\mathrm{GEN}}$</td></tr>
</table>

The set of all higher-order operations Λ



indefinite causal order

Transform channels into channels



Upper bound for unitary discrimination

$$P^{GEN} \leq \frac{1}{N} \frac{(k+d^2-1)!}{k!(d^2-1)!}$$

SKETCH OF PROOF: analytically exhibit a feasible point in the dual problem of the maximal probability of discrimination attained by general strategies; this induces an upper bound for all strategies.

More concrete problems

1 Research Line 1

- Potential impossibility of universally transforming general operations into unitary operations (dilation)
- Optimal circuits (in terms of number of calls) for unitary inversion and transposition
- Optimal strategies for channel discrimination and metrology asymptotically; under constraints

2 Research Line 2

- Upper and lower bounds for quantum query complexity of simulating the quantum switch
- Computational tasks where indefinite causal order is advantageous

3 Research Line 3

- Activation of Bell nonlocality through catalysis
- Bell nonlocality in networks under weaker device-dependence assumptions
- Certification of many-party higher-order processes for quantum networks