Decoding quantum information from chaos

beyond the standard situation

Yoshifumi Nakata

(YITP, Kyoto University)

Quantum Information is an **interdisciplinary field** between **Physics** and **Computer Science.**

10-15 years ago

Computer Science

- Computing
- Error Correction
- Non-locality and security
- Complexity problem

- Topological order
- Thermalization
- Entanglement
- Q field theory

Quantum Information

Physics

Quantum Information is an **interdisciplinary field** between **Physics** and **Computer Science.**

Currently....

Computer Science

Fault-Tolerant Quantum Computation

Quantum Communication

Quantum Internet

Quantum Cryptography

Quantum Information

Simulating quantum systems,
e.g. QCD, high energy physics, etc..

Physics

Quantum Information as a Tool.

“Quantum Information is an **interdisciplinary field** between Physics and Computer Science.

Currently....

Physically-relevant
Quantum Error Correction

There are still many things in Quantum Information that can be explored **based on the physics intuition.**

Quantum Cryptography

Simulating quantum systems,
e.g. QCD, high energy physics, etc..

We may use quantum technology to better understand physics.

Quantum Information

Computer

Physics

Outline

1. **Introduction:** **Quantum Error Correction & physics**
2. **Decoding the Hayden-Preskill protocol**
3. **Conclusion**


arXiv > quant-ph > arXiv:2210.06661

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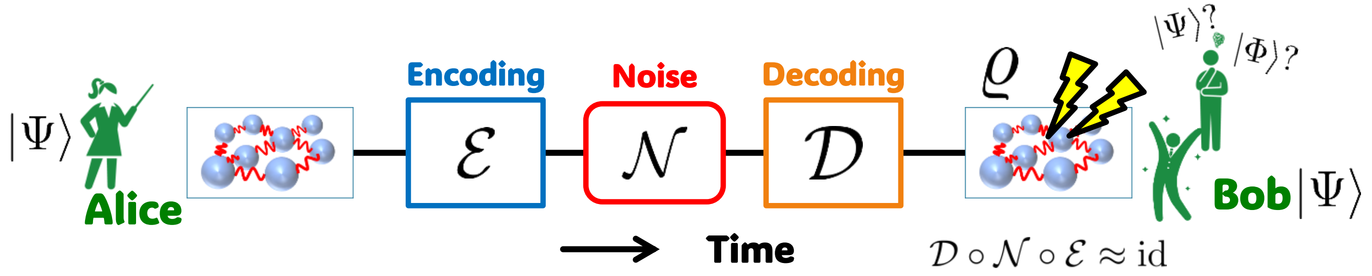
1.

Introduction

1. The ABC's of Quantum Error Correction (QEC)
2. Why should we, physicists, care about QEC?

Introduction - Quantum Error Correction -

- *Quantum Error Correction (QEC)* is a method to effectively cancel noise in a quantum system.
  - QEC is a key to achieve ***a large-scale quantum information processing***.
  - Growing interest in theoretical physics.
    - ***Quantum gravity***, ***quantum chaos***, and ***new quantum phases*** related to QEC.



Quantum Error Correcting Code (QECC) = $(\mathcal{E},\mathcal{D})$

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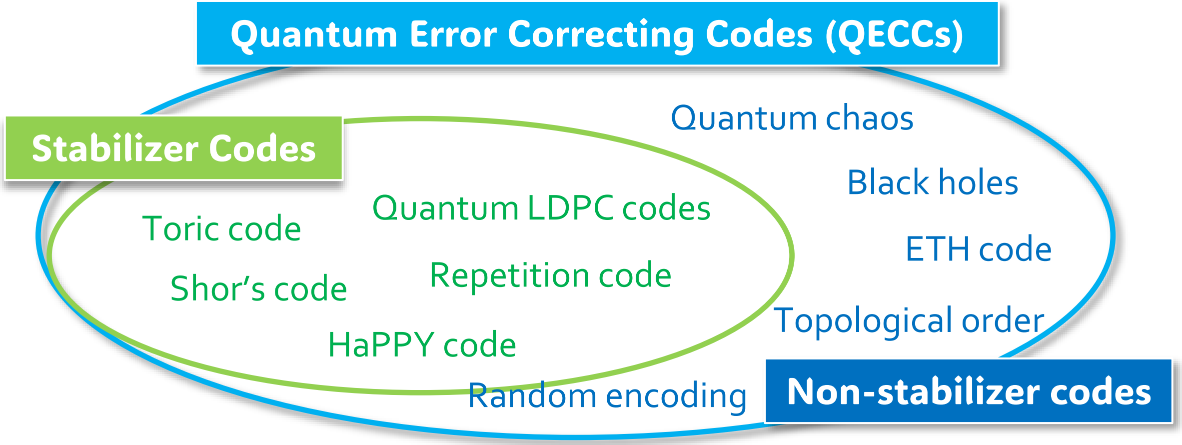

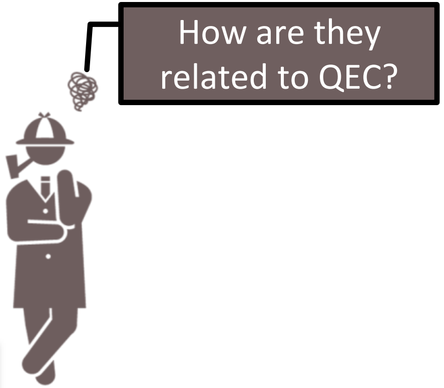

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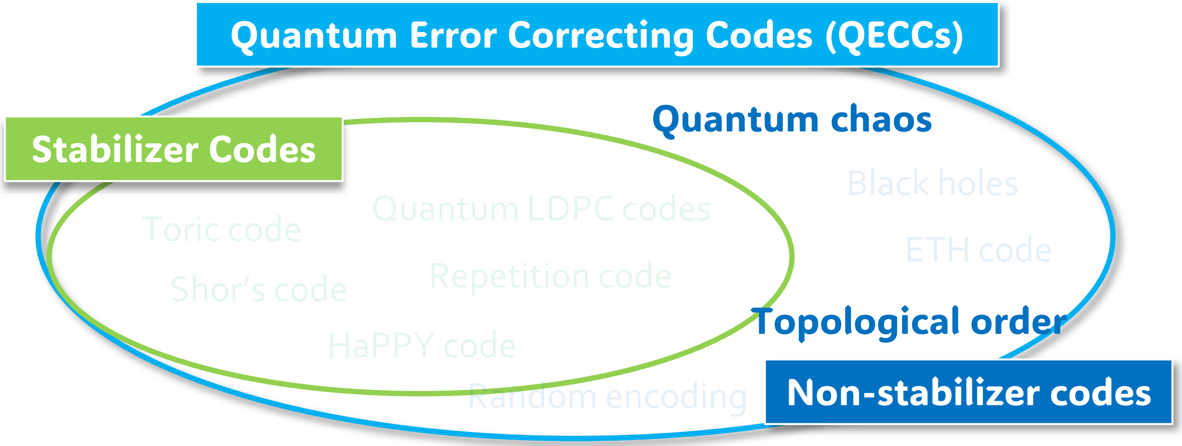
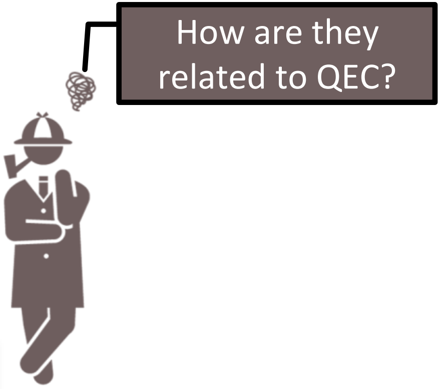
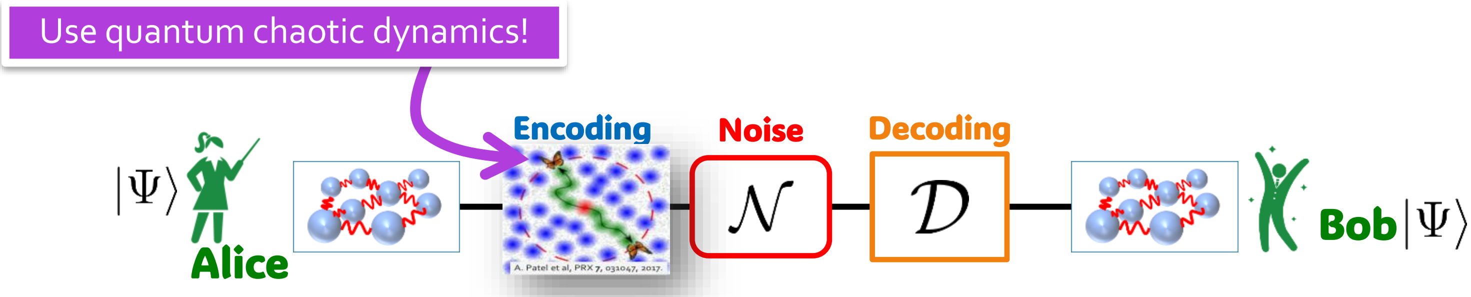




Introduction - QEC and Quantum Chaos -

- The idea is to use chaotic dynamics for encoding quantum states.

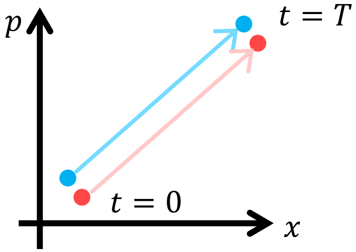


Introduction - QEC and Quantum Chaos -

- The idea is to use **chaotic dynamics** for **encoding** quantum states.
- **Chaotic dynamics** is sensitive to initial conditions (at least classically).

Phase space

Simple dynamics
(e.g. integrable)



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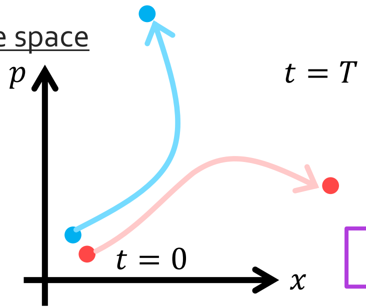
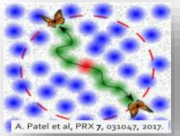
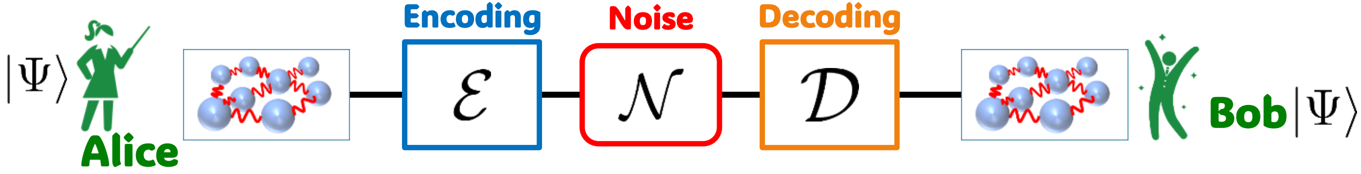


Chaotic dynamics





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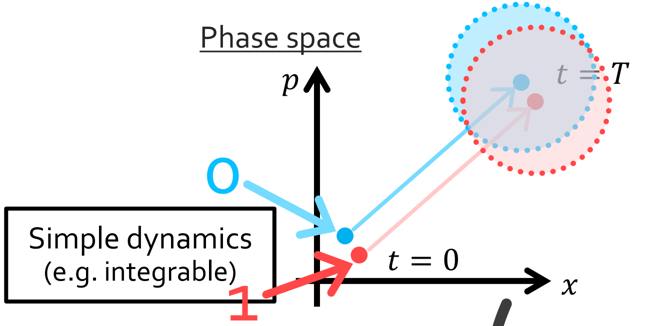
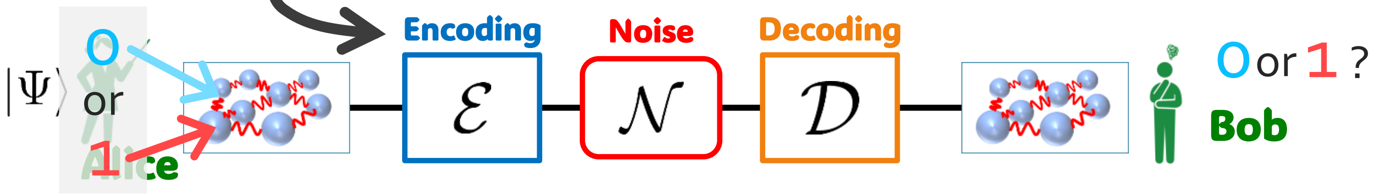


1. Encode 0 or 1 into an initial condition.
2. It undergoes the time evolution.
3. It is "*distorted*" by the **noise**.
4. Huge overlap!! The *distorted* 0 and 1 are indistinguishable.

→ **Decoding** will **NOT** be possible.



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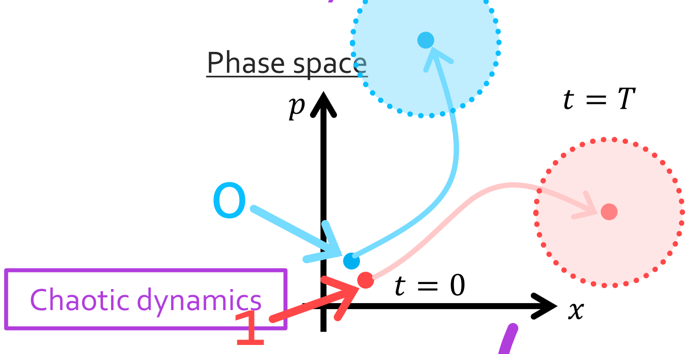
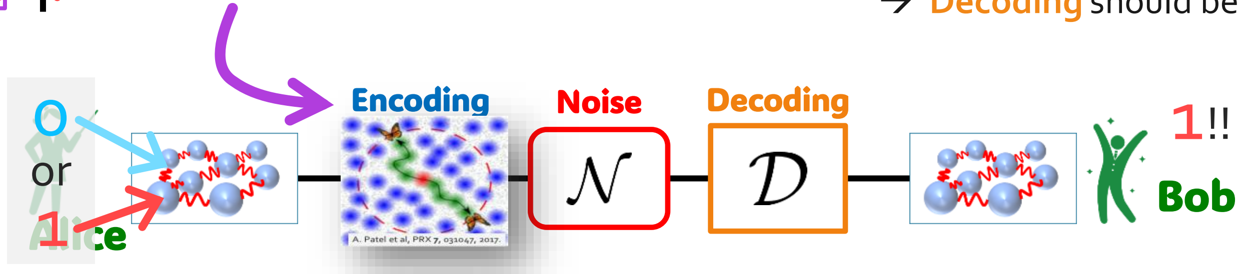


1. Encode 0 or 1 into an initial condition.
2. It undergoes the **chaotic** time evolution.
3. It is "*distorted*" by the **noise**.
4. No overlap!! The *distorted* 0 and 1 are distinguishable.

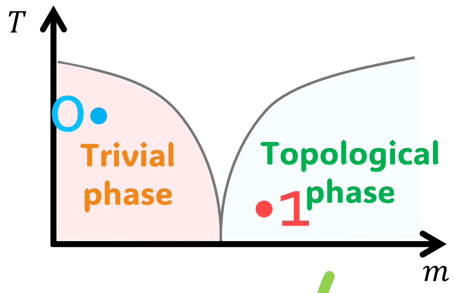
→ **Decoding** should be possible.



Introduction - QEC and Topological Order -

- Similarly, we can use a **topological order** for **encoding** quantum states.

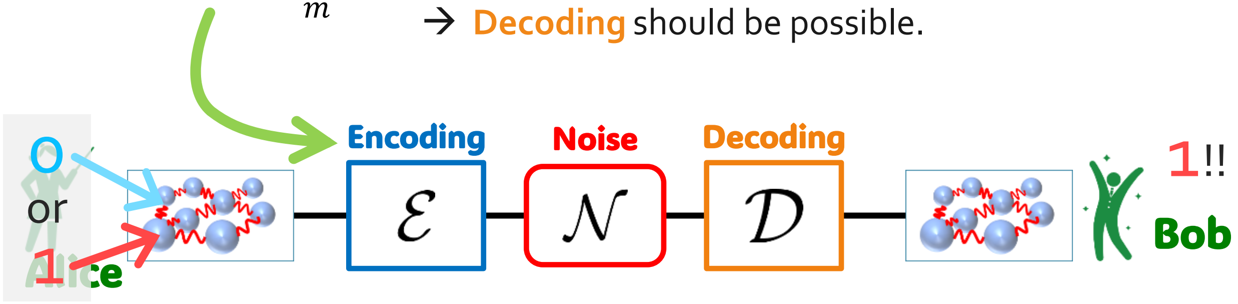
Phase diagram



1. Encode 0 into a state in a topological phase and 1 into a state in a trivial phase.
2. **No local noise** can change the phase.

→ The information 0 and 1 is protected by the **topological order**.

→ **Decoding** should be possible.



Introduction - QEC in Physics -

- ☐ Chaotic dynamics is sensitive to initial conditions (at least classically).
- ☐ Topological order is not broken by local operations.

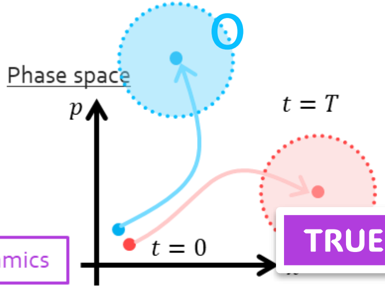
→ **Physics intuition is useful for constructing QECCs!**

- ☐ **Caution!**

1. QUANTUM case is not so trivial due to, e.g., **coherence** ($\alpha|0\rangle + \beta|1\rangle$,not 0 or 1).
2. Unitary dynamics does **NOT** change the distance.

By sharpening the intuition, they are turned out to be useful for QEC with suitable settings.

Chaotic dynamics



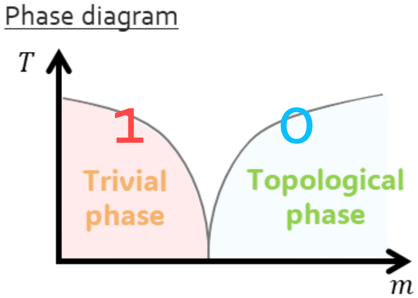
Random encoding

[Lloyd, '97] [Shor, '02] [Devetak, '05]

Hayden-Preskill model

[Hayden & Preskill, '07]

TRUE for a Haar random dynamic



Kitaev's toric code

[Kitaev, '97]

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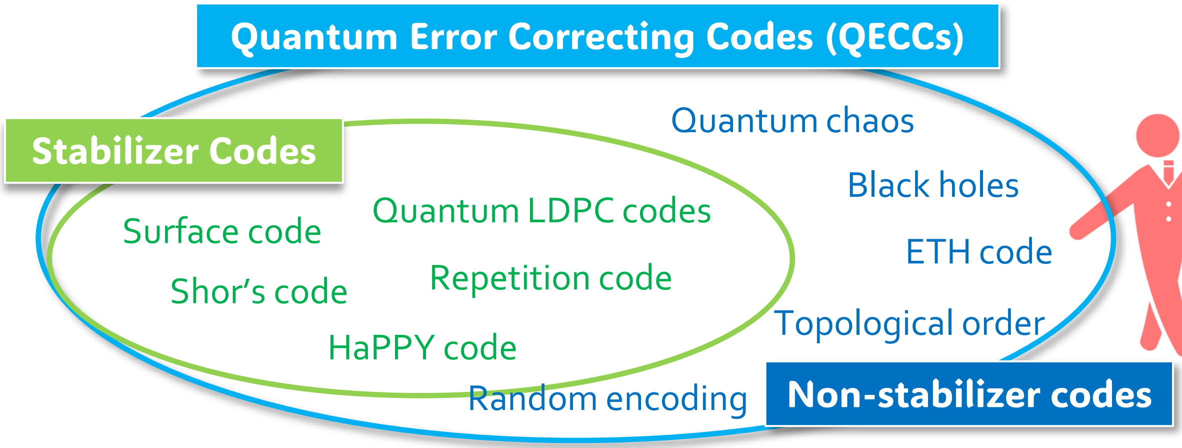

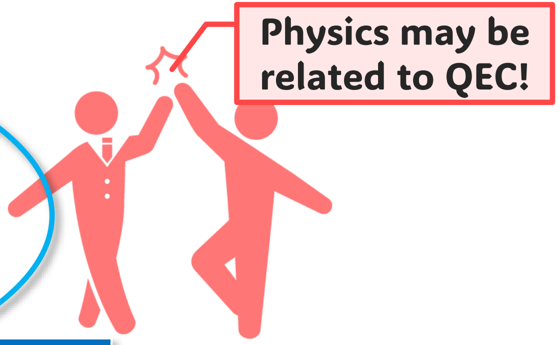

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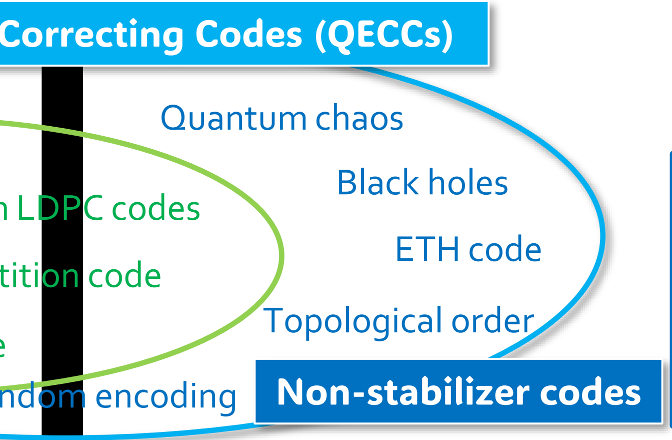

In this talk, we will focus on non-stabilizer codes.

Features of non-stabilizer codes

☺ Many *physically-relevant QECCs*.

☺ They sometimes have better code performance than stabilizer ones.

☹ **Not as simple as stabilizer codes.**

→ In particular, *decoding* is highly non-trivial.

Introduction - Decoding non-stabilizer codes -

- Recently, I have been working on **the decoding problem** of **non-stabilizer codes**.

arXiv > quant-ph > arXiv:2210.06661

Quantum Physics

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- Based on the **complementarity principle.**
- Construct a decode from two "classical decoders".

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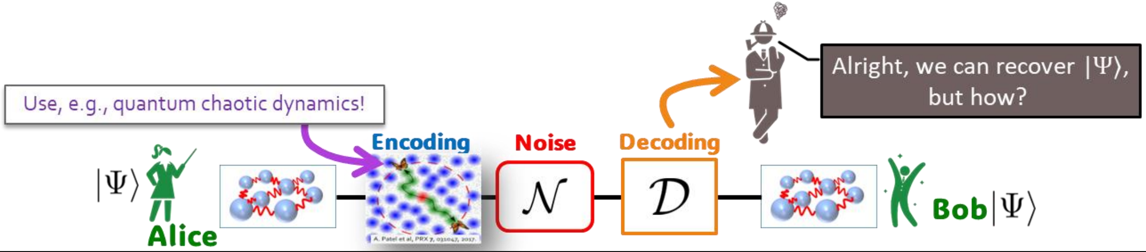
Explicit decoders using fixed-point amplitude amplification based on QSVT

Takeru Utsumi, Yoshifumi Nakata

- Clever use of a **quantum algorithm** (QSVT).
- Generalization of the Yoshida-Kitaev decoder.



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- Construct a decode from two "classical decoders".

We will focus on this construction and demonstrate it in a toy model of QEC, that is, the Hayden-Preskill model.

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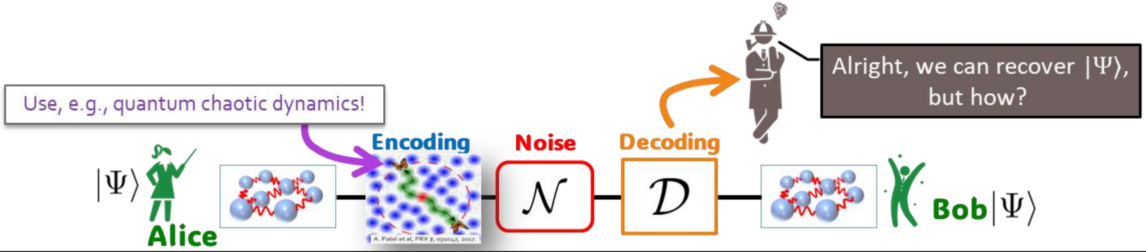
Quantum Physics

- Generalization of the Yoshida-Kitaev decoder.



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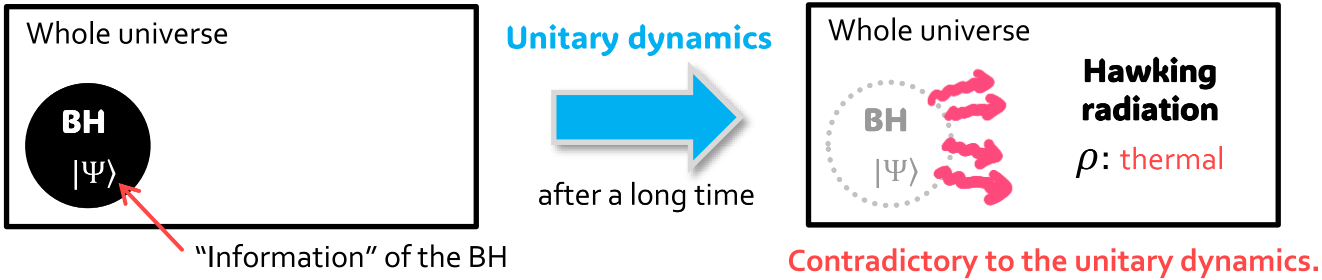
Decoding the Hayden-Preskill

- What is the **Hayden-Preskill model**?
  - A (oversimplified) toy model of **the black hole information paradox**

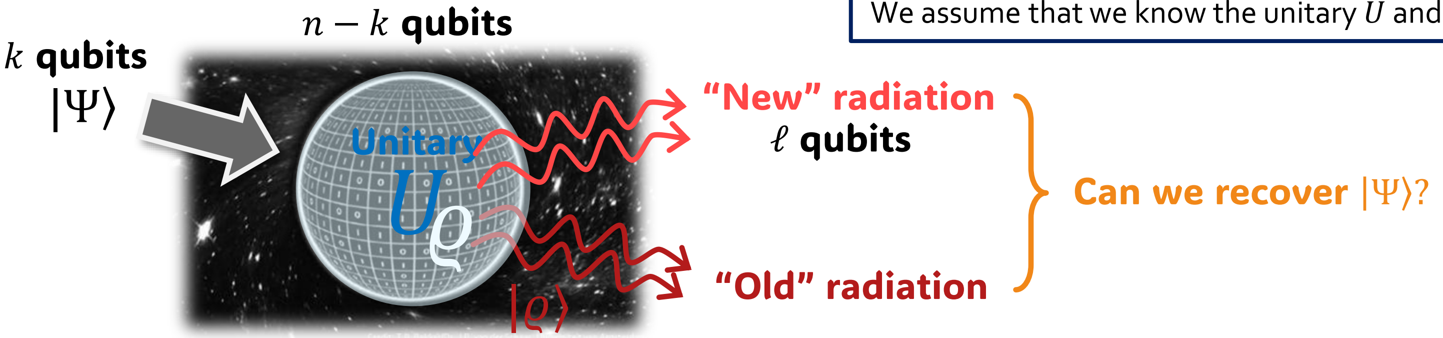


  - If we believe **unitarity**, the "information" of the BH should be recoverable from the radiation.
  - **Motivation of the Hayden-Preskill: how much radiation is needed for the recovery?**

Decoding **the** **Hayden-Preskill**

- What EXACTLY is the **Hayden-Preskill model**?
  - A (oversimplified) toy model of **the black hole information paradox**

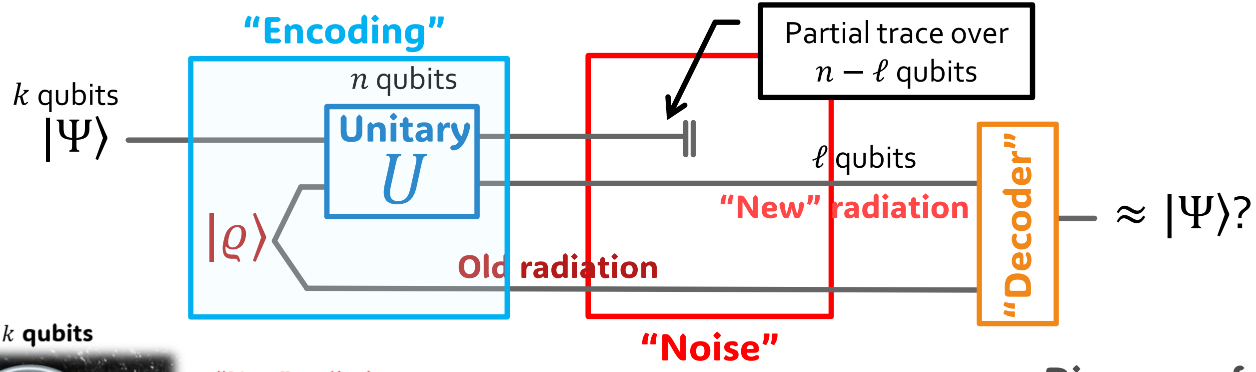
We assume that we know the unitary U and $|\varrho\rangle$.

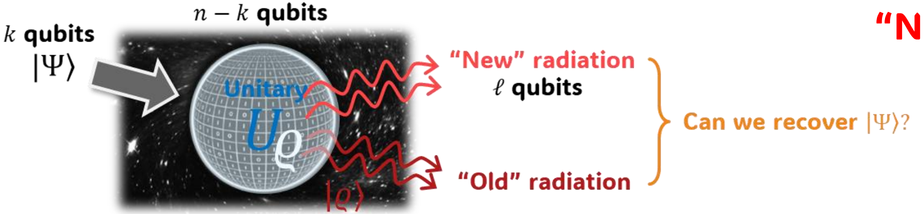


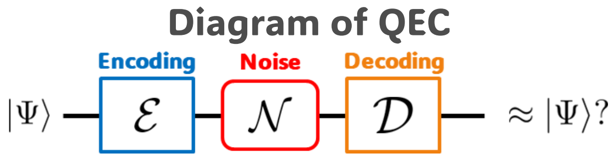
  - If $\ell = n$, $|\Psi\rangle$ is recovered by $U^\dagger$.
  - How large should ℓ be for the recovery of the k-qubit state $|\Psi\rangle$ to be possible?

Decoding the Hayden-Preskill

- What EXACTLY is the **Hayden-Preskill model**?
  - A (oversimplified) toy model of **the black hole information paradox**
  - The Hayden-Preskill model is also a simple toy model of QEC.







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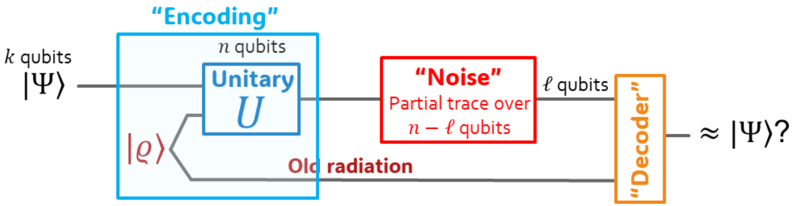
  - A (oversimplified) toy model of **the black hole information paradox**
  - The Hayden-Preskill model is also a simple toy model of QEC.
    1. **Encoding** = "BH unitary dynamics"
    2. **Noise** = the partial trace over $n-\ell$ qubits

- Hayden & Preskill used a standard QEC technique, and showed the following.

If U is Haar random $\Rightarrow$ the recovery error $\Delta \leq 2^{\frac{\ell_{th}-\ell}{2}}$ where $\ell_{th} = (n+k-H_2(\varrho))/2$.



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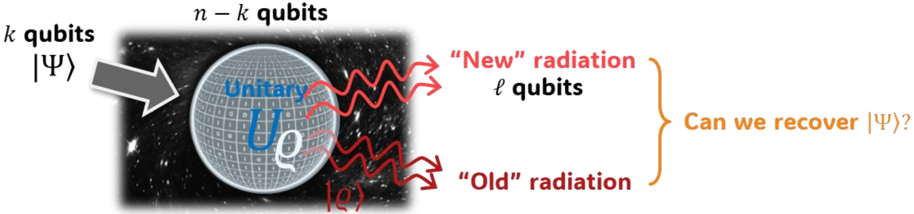
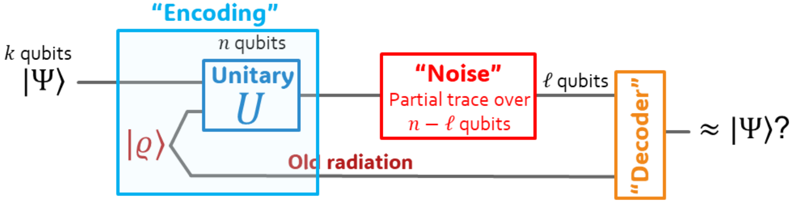
> If U is Haar random $\Rightarrow$ the recovery error $\Delta \leq 2^{\frac{\ell_{th}-\ell}{2}}$ where $\ell_{th} = (n+k-H_2(\varrho))/2$.

  - Dep. on the initial entropy of the BH, ℓ_{th} ranges from k (for max entropy) to $(n+k)/2$ (for zero entropy).
  - Unfortunately, the proof does not EXPLICITLY provide a decoder.

How can we explicitly "decode" the Hayden-Preskill protocol?





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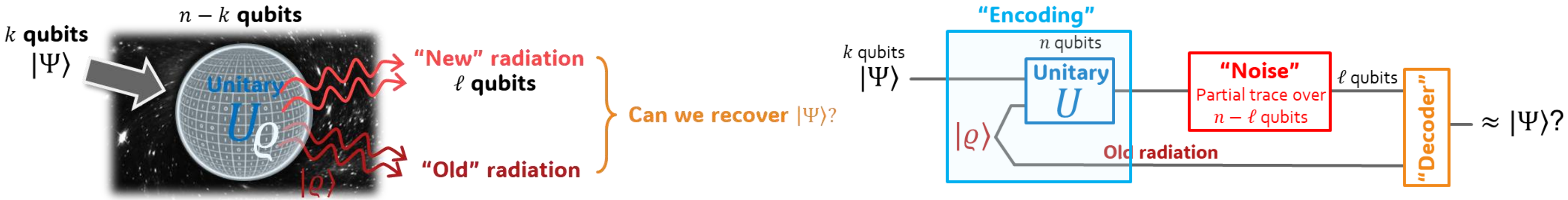
1. **The Petz recovery map** [Barnum & Knill, JMP '02]

   Good: it works for ***any noise***.
   Bad: ***inefficient***, and too complicated to improve the construction.

2. **Yoshida-Kitaev decoder** [Yoshida & Kitaev, '17]

   Good: **Clear Q. circuit** construction.
   Bad: ***inefficient***, and ***works only for decoding the Hayden-Preskill protocol***.



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Non-trivial upgrade!

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3. **Classical-to-Quantum decoder** [YN, Matsuura & Koashi, '22]

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   Bad: ***inefficient***.

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   Good: Reduces the problem to a CLASSICAL one (= hopefully easy to improve), and works for ***any noise***.
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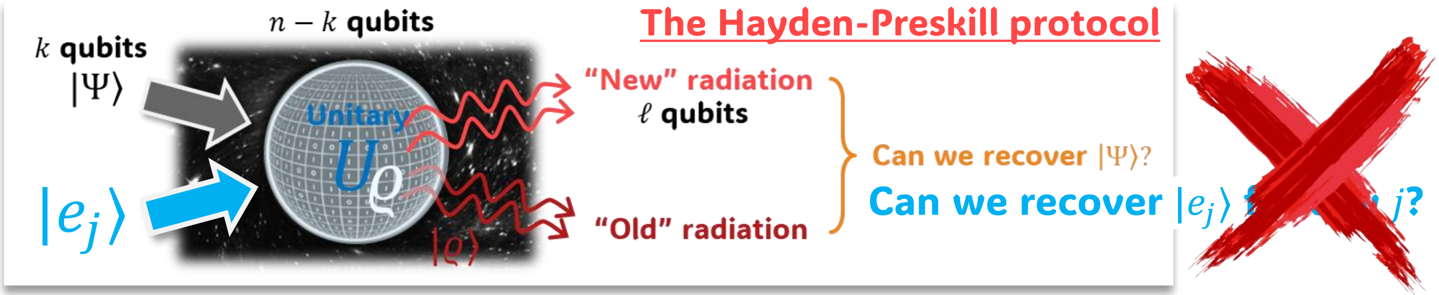
The decoder works for any noise, but we'll focus on the HP protocol.

Classical-to-Quantum decoder

- Goal: to construct a **decoding quantum circuit** for general **QECCs**, incl. the Hayden-Preskill.
  - **A difficulty**: need to consider **ALL** state $|\Psi\rangle \in \mathcal{H}^A$.
    - $|\Psi\rangle = c_1|e_1\rangle + c_2|e_2\rangle + \cdots + c_{2^k}|e_{2^k}\rangle$, where $\{|e_j\rangle\}_j$ is a basis.
  - Enough to consider **basis states** $\{|e_j\rangle\}_j$? **Answer: No, it's not enough.**



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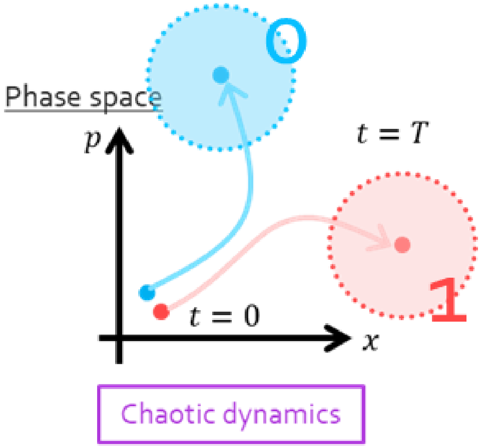

$|0\rangle$ or $|1\rangle$ can be recovered.

But, coherence ($\alpha|0\rangle + \beta|1\rangle$) may not.

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  - **A difficulty**: need to consider **ALL** state $|\Psi\rangle \in \mathcal{H}^A$.
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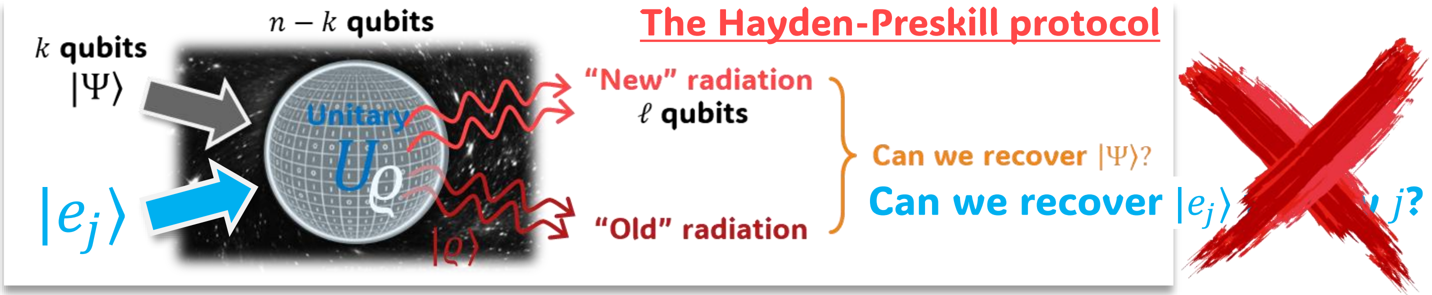
  - Enough to consider **basis states** $\{|e_j\rangle\}_j$? **Answer: No, it's not enough.**
    - Recovery of a basis $\not\Rightarrow$ *superposition (coherence)* maintained.

Use the complementarity principle of quantum theory!



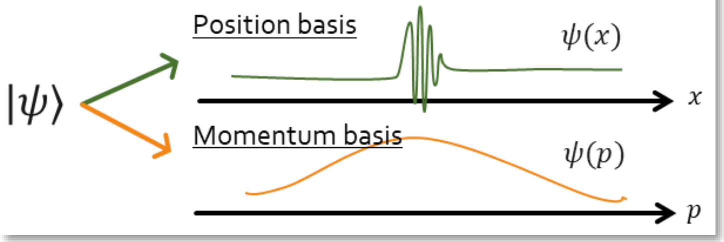
Classical-to-Quantum decoder

- Goal: to construct a **decoding quantum circuit** for general **QECCs**, incl. the Hayden-Preskill.

Use the complementarity principle of quantum theory!

- If **one observable** is **definite**, its **complementary counterpart** is **indefinite**. Hence, two complementary observables are necessary to FULLY describe a quantum system.
- If we can decode "**a pair of complementary bases**", we may decode any state $|\Psi\rangle \in \mathcal{H}^A$!

Complementarity of a wave function



A pair of complementary bases

Eigenbasis of the Pauli Z $=\{|0\rangle, |1\rangle\}$

Eigenbasis of the Pauli X $=\{|+\rangle, |-\rangle\}$

$$|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

Classical-to-Quantum decoder

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  - If we can decode "**a pair of complementary bases**", we CAN decode **any state** $|\Psi\rangle \in \mathcal{H}^A$!

Original setting

A basis $E = \{|e_j\rangle^A\}_{j=1,\dots,2^k}$

Turns out to be equivalent!!

Complementary basis $F = \{|f_\alpha\rangle^A\}_{\alpha=1,\dots,2^k}$

How can we decode a basis-state?

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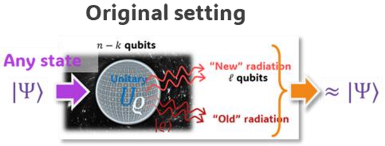
  - The input is one of the 2^k basis states $\{|e_j\rangle\}_{j=1,\dots,2^k}$. Enough to identify **the labelling $j \in \{1, \dots, 2^k\}$**.



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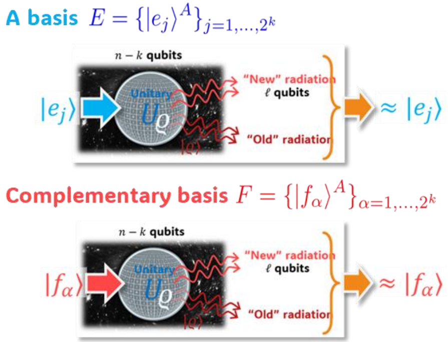

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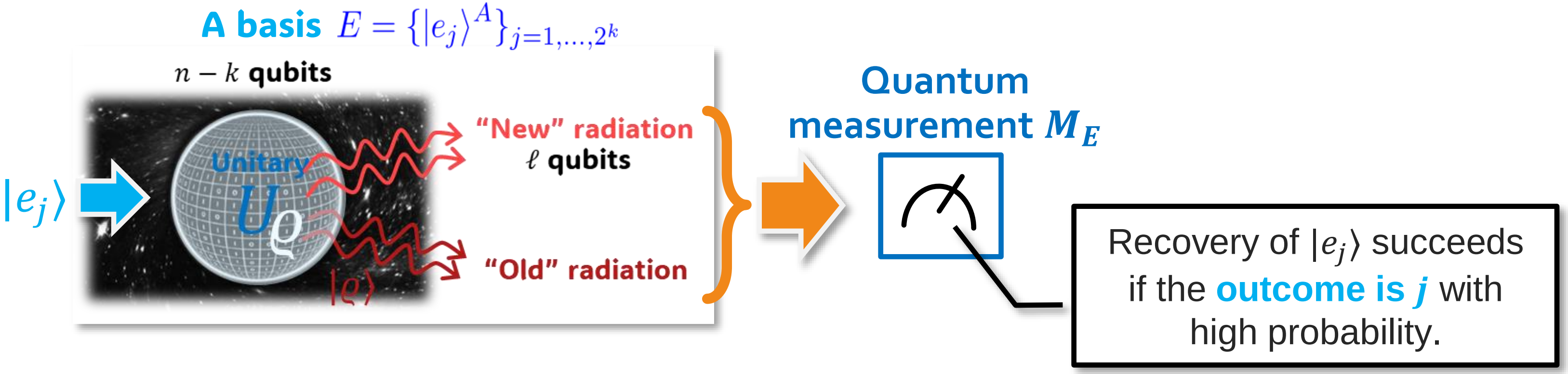

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Original setting

$\Longleftrightarrow$

A basis $E = \{|e_j\rangle^A\}_{j=1,\dots,2^k}$

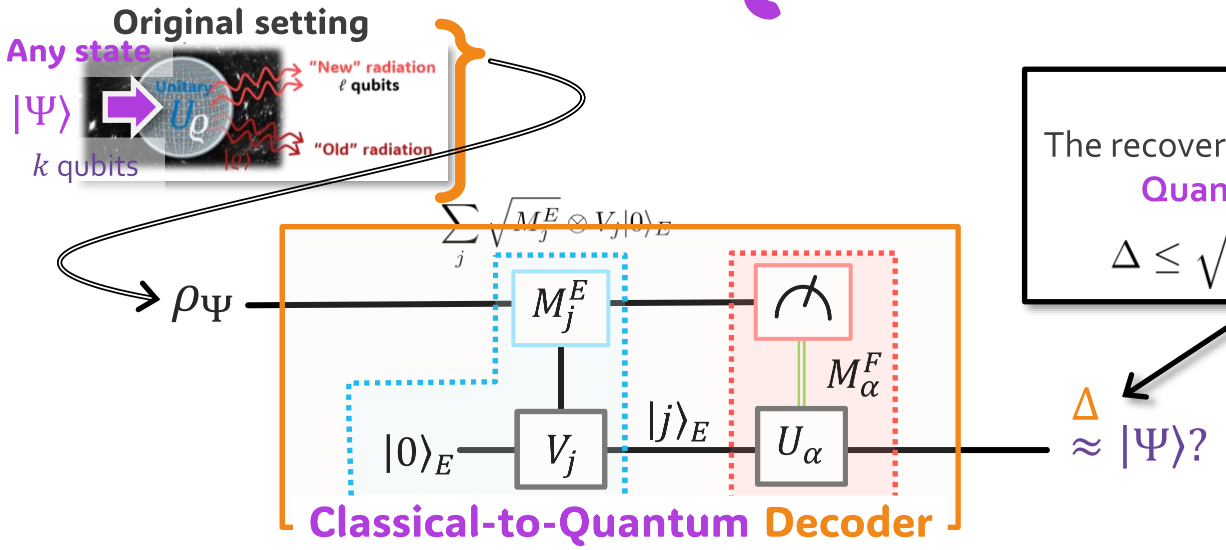
Quantum measurement M_E

Complementary basis $F = \{|f_\alpha\rangle^A\}_{\alpha=\dots}$

Quantum measurement M_F

It should be possible to construct a decoder from two quantum measurements.

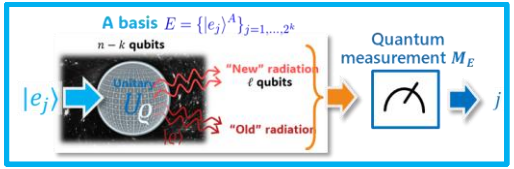
Classical-to-Quantum decoder



Theorem

The recovery error Δ of the Classical-to-Quantum decoder satisfies

$$\Delta \leq \sqrt{P^E_{\rm fail}(2-P^E_{\rm fail})} + \sqrt{P^F_{\rm fail}}$$

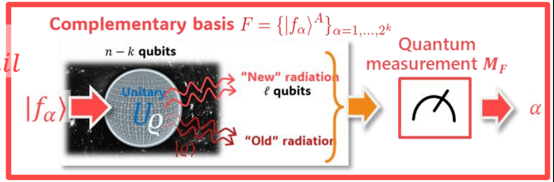


$M_E = \{M_j^E\}_j$

Failure probability P^E_{fail}

Failure probability P^F_{fail}

$M_F = \{M_\alpha^F\}_\alpha$



Classical-to-Quantum decoder

- Based on the complementarity idea, a decoder can be constructed.
  - If two good Q measurements are given, recovering the complementary bases, we can EXPLICITLY construct a good decoder.
    - ∃standard approach to find such good Q measurements → our decoder is ***near optimal***.

      ➡ Unfortunately, **no efficient construction** is known…, need an improvement.
- This decoder works for ANY encoding and noise.

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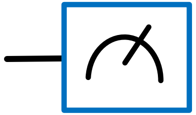
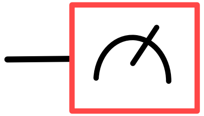
Quantum measurement M_E for a basis E.



Failure probability P^E_{fail}

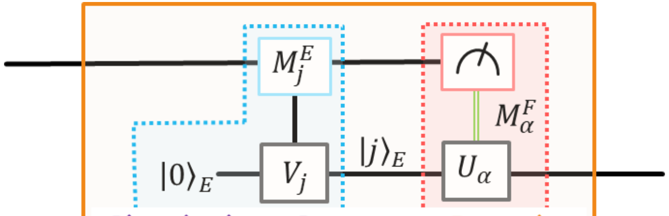
×

Quantum measurement M_F for a complementary basis F.



Failure probability P^F_{fail}

=



Classical-to-Quantum Decoder

Classical-to-Quantum decoder

- Based on the **complementarity** idea, a **decoder** can be constructed.
  - If **two good Q measurements** are given, recovering the complementary bases, we can EXPLICITLY construct a **good decoder**.
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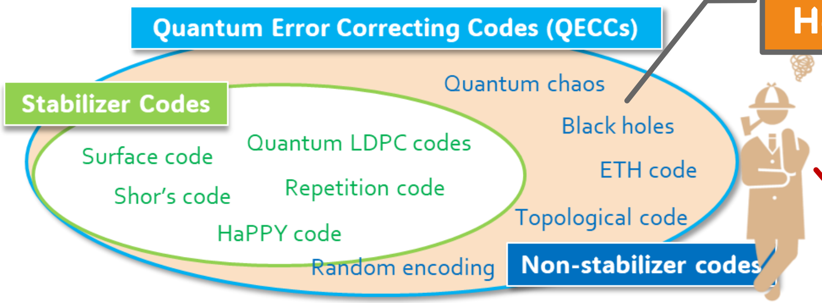


How can we decode non-stabilizer codes?

Answer: enough to find two Q measurements for recovering complementary bases.

Can we find EFFICIENT measurements?

Classical-to-Quantum decoder

- Based on the complementarity idea, a decoder can be constructed.
  - The recovery error of the decoder is given by the failure probabilities of the two Q measurement

1. **The Petz(-like) recovery map** [Barnum & Knill, JMP '02] [Utsumi & Nakata, '24]
   Good: it works for *any noise*.
   Bad: *inefficient*.
   → **Could be improved, but needs full Q analysis.**

2. **(generalized) Yoshida-Kitaev decoder** [Yoshida & Kitaev, '17] [Utsumi & Nakata, '24]
   Good: Clear Q. circuit construction and works for *any noise*.
   Bad: *inefficient*.
   → **Can NOT be improved.** **PROVEN**

3. **Classical-to-Quantum decoder** [YN, Matsuura & Koashi, '22]
   Good: From CLASSICAL ones, and works for *any noise*.
   Bad: *inefficient*.
   → **Could be improved, and Classical analysis suffices.**

HaPPY code

Random encoding

Non-stabilizer codes

Can we find EFFICIENT measurements?

Outline

1. Introduction: Quantum Error Correction & physics
2. Decoding the Hayden-Preskill model
3. **Conclusion**

arXiv > quant-ph > arXiv:2210.06661

Quantum Physics

[Submitted on 13 Oct 2022 (v1), last revised 25 Jun 2024 (this version, v4)]

Decoding general error correcting codes and the role of complementarity

Yoshifumi Nakata, Takaya Matsuura, Masato Koashi

[YN, T. Matsuura, and M. Koashi, 2210.06661 (2022)]

arXiv > quant-ph > arXiv:2405.06051

Quantum Physics

[Submitted on 9 May 2024 (v1), last revised 9 Oct 2024 (this version, v3)]

Explicit decoders using fixed-point amplitude amplification based on QSVT

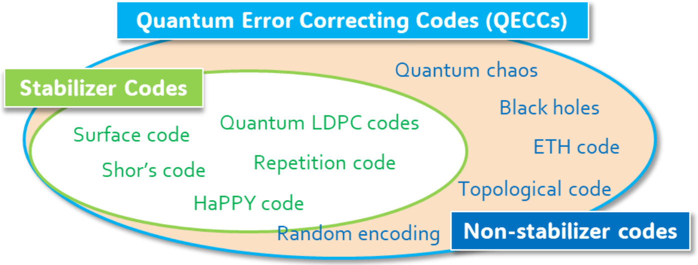
Takeru Utsumi, Yoshifumi Nakata

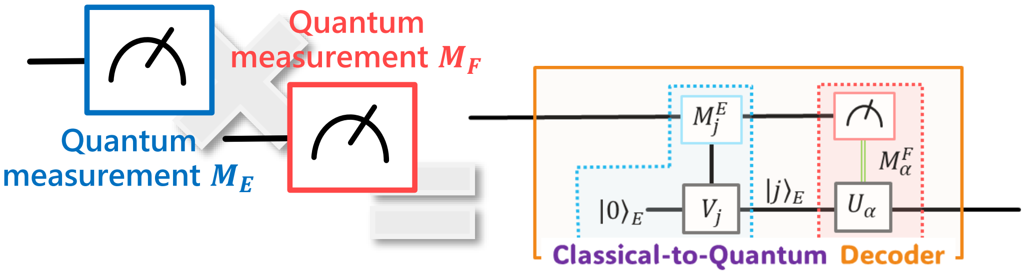
[T. Utsumi & YN, 2405.06051 (2024)]

Conclusion

- **There are many QECCs that are related to complex physics phenomena.**
  - They are usually **non-stabilizer codes**, so **decoding** is highly non-trivial.
- **The complementarity principle helps the decoding problem**
  - From **two Q measurements** for a pair of **complementary bases**, a **decoder** can be explicitly constructed.

∃Many topics in Quantum Information that we can explore based on the physics intuition.





Thank you for listening!

[YN, T. Matsuura, and M. Koashi, 2210.06661 (2022)]

Special thanks to

- Human pictgram 2.0
- Credit: T.B. Bakker/Dr. J.P. van der Schaar, Universiteit van Amsterdam for the figure of a black hole.
- “Quantum Butterfly Effect in Weakly Interacting Diffusive Metals” by A. A. Patel, D. Chowdhury, S. Sachdev, and B. Swingle, PRX 7, 031047 (2007) for the figure of chaos.