GSoC 2025 Proposal: Create and add to an example gallery for `toqito`

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1. Introduction and Motivation

I am a Computer Science graduate from Bangladesh and a dedicated quantum computing enthusiast applying for the `toqito`: **Create and add to an example gallery** project under `NumFOCUS` for GSoC 2025. While my undergraduate studies didn't formally include quantum computing, I have actively developed a deep interest and foundational knowledge in the field over the last year through dedicated self-study.

My learning journey has encompassed diverse resources, including:

- **Structured Platforms:** IBM Quantum Experience learning platform.
- **Community Workshops:** QWorld workshops (successfully completed a QBronze Diploma, currently progressing through QNickel).
- **Core Texts:** Foundational books like Nielsen & Chuang's "Quantum Computation and Quantum Information," Yanofsky & Mannucci's "Quantum Computing for Computer Scientists," supplemented by resources like Gilbert Strang's Linear Algebra lectures and insightful visualizations like the "Maths of Quantum Mechanics" series.
- **Practical Application:** Developing personal quantum computing projects. (Github)
- **Independent Research:** Focused on quantum digital signatures in the context of cloud data security.

I discovered `toqito` a little over a month ago and was immediately impressed by its focus on quantum information theory research tools. Seeing references to John Watrous's work, whose TQI lectures I consider an excellent resource, further solidified my interest in contributing to this specific library. My goal is not only to successfully complete this GSoC project but also to become a long-term contributor, helping improve `toqito`'s quality and promote its adoption within the research community.

2. Demonstrated Engagement and Capability within `toqito`

I have already begun contributing to `toqito` to familiarize myself with the codebase, contribution standards, and community interaction (primarily via GitHub).

- **Merged PR #1047: Implement `is_extremal` function and tests**
  - Implemented the `is_extremal` function within `channel_props`, based on Watrous's *Theory of Quantum Information*. Added comprehensive tests covering various channel types (unitary, non-extremal, Choi matrix input) and supported multiple channel representations.
- **Merged PR #1075: Update docstrings in `matrix_ops/vec.py`**
  - Corrected technical inaccuracies in function descriptions and mathematical examples within the documentation for the 'vec' operator.

- **Ongoing Contribution: Porting QETLAB's Bell Inequality Calculation** (Work in progress on Issue #1049)
  - Currently working on implementing functionality to compute the maximum value of a Bell inequality, drawing inspiration from the established QETLAB library.

3. Project Suitability and Commitment

I am applying for the Example Gallery project because it perfectly combines my interest in quantum information theory, my software development skills (Python), and my desire to make `toqito` more accessible. My qualifications and commitment make me confident in my ability to successfully complete this project:

- **Technical Foundation:** My Computer Science degree provides a solid base in programming (Python) and software development practices. This was further solidified during my remote Software Developer internship at Itransition Group, improving my skills in professional workflows and remote collaboration. My self-study has equipped me with the necessary quantum information concepts and linear algebra (utilizing resources like Gilbert Strang's lectures and book).
- **Proven `toqito` Experience:** I believe my merged PRs show that I can navigate the `toqito` codebase, understand its quantum information focus (channels, matrix operations), adhere to its coding standards, and effectively use the Git/GitHub workflow for contribution and review.
- **Alignment with Project Goals:** The `is_extremal` PR (#1047) is directly related to the proposed Examples 5 & 6. My documentation PR (#1075) shows my ability to produce clear explanations, which is important for the example gallery content. My ongoing work touches on areas relevant to other `toqito` modules.
- **Time Commitment:** I am prepared to dedicate myself **full-time (approximately 40 hours per week)** to this GSoC project for the entire duration (approx. 12 weeks for a 225-hour project). I currently have following minor commitments, which will not interfere: e.g., <2 hr/week for BeyondQuantum support as a volunteer till June 1st. I understand this is a paid role requiring significant, consistent effort.
- **Adherence to GSoC Practices:** I have carefully reviewed the GSoC evaluation criteria and am committed to maintaining **regular communication** (daily check-ins via Discord as suggested by `toqito`, bi-weekly blog posts), **frequent code commits** ("commit early, commit often" to a public repository), and actively participating in the **code review process** to meet the evaluation and merge requirements.

4. Contact Information)

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5. Link to Application File

- All application materials, including this proposal document, can be accessed at this GitHub repository

6. Proposed Project Deliverables: `toqito` Example Gallery and Content

This project aims to create a user-friendly example gallery for `toqito`, inspired by the structure and utility of the scikit-learn examples page. This involves two primary components:

1. **Gallery Infrastructure:** Developing the gallery webpage structure itself, ensuring it integrates well with `toqito`'s existing documentation (e.g., potentially using Sphinx-Gallery), displays examples clearly (e.g., using tiled thumbnails), and links correctly to individual example pages/scripts.
2. **Example Content:** Populating the gallery with a set of high-quality, well-documented, standalone Python examples demonstrating key `toqito` functionalities, particularly in areas identified as gaps in the GSoC project description.

Core Example Deliverables (Target: 6 Examples)

The following six examples represent the core deliverables for this project, ensuring coverage of the specific areas requested by `toqito`. Each example will include a self-contained Python script and accompanying documentation explaining the scenario, the `toqito` implementation, and the interpretation of the results.

(A) `ExtendedNonlocalGame` for QKD/BC Use Cases

- **Example 1: Modeling Bit Commitment Hiding Failure using `ExtendedNonlocalGame`**
  - **Objective:** Demonstrate how `toqito.nonlocal_games.ExtendedNonlocalGame` can model and quantify the "hiding" vulnerability in a quantum bit commitment (BC) protocol.
  - **Key `toqito` Usage:** Instantiating `ExtendedNonlocalGame`, customizing the prediction matrix (`pred_mat`) and probability matrix (`prob_mat`) to model the BC scenario, using `game.quantum_value_lower_bound()` to calculate Bob's cheating probability. May use `toqito.states` for state definitions.
  - **Value:** Showcases non-trivial ENLG customization for a cryptographic application, provides pedagogical insight into BC security limits.
- **Example 2: Analyzing QKD QBER Bounds using `ExtendedNonlocalGame`**
  - **Objective:** Show how `ExtendedNonlocalGame` can analyze eavesdropping impact in QKD (specifically BB84 parameter estimation) by bounding the Quantum Bit Error Rate (QBER) derivable from protocol statistics.
  - **Key `toqito` Usage:** Instantiating `ExtendedNonlocalGame`, customizing `pred_mat` to detect error events relevant to QBER, using bounds like `game.nonsignaling_value()` or `game.commuting_measurement_value_upper_bound()` to find the maximum possible error rate.
  - **Value:** Connects the abstract ENLG framework to concrete QKD security analysis, demonstrates calculating security bounds.

(B) Quantum State Antidistinguishability Examples (from Literature)

- **Example 3: Testing the Antidistinguishability Threshold for Equiangular States**
  - **Objective:** Numerically verify the sharp antidistinguishability threshold for n equiangular pure states presented in arXiv:2311.17047 (Cor 4.2).
  - **Key `toqito` Usage:** Constructing Gram matrices, generating state vectors using `toqito.matrix_ops.vectors_from_gram_matrix`, and verifying the threshold using `toqito.state_opt.state_exclusion(strategy="min_error")`.
  - **Value:** Directly addresses GSoC goal using specified literature, demonstrates `state_opt` module, showcases verification of theoretical bounds.

- **Example 4: Antidistinguishability of Circulant States using the Eigenvalue Criterion**
  - **Objective:** Investigate antidistinguishability for circulant states using the necessary and sufficient eigenvalue condition from arXiv:2311.17047 (Thm 5.1).
  - **Key `toqito` Usage:** Generating circulant Gram matrices with `toqito.rand.random_circulant_gram_matrix`, obtaining states via `toqito.matrix_ops`, computing eigenvalues (e.g., via `numpy.linalg`), checking the analytical condition, and comparing with `toqito.state_opt.state_exclusion(strategy="min_error")`.
  - **Value:** Addresses GSoC goal with literature example, connects structural properties (circulant) to analytical conditions and `state_opt` computation, uses `rand` module.

(C) Flesh out Existing Topics (`toqito.channel_props`)

- **Example 5: Verifying Extremality of Unitary Channels**
  - **Objective:** Demonstrate `toqito.channel_props.is_extremal` correctly identifying unitary channels (a fundamental class of extremal channels) as extremal.
  - **Key `toqito` Usage:** Defining a unitary using `toqito.matrices`, converting to Choi representation using `toqito.channel_ops.kraus_to_choi`, and applying `toqito.channel_props.is_extremal`.
  - **Value:** Fills a documentation gap for `channel_props`, confirms function aligns with theory, illustrates a basic practical workflow (matrix -> channel op -> channel prop).
- **Example 6: Identifying Non-Extremal Channels (e.g., Depolarizing Channel)**
  - **Objective:** Contrast with Example 5 by showing `is_extremal` correctly identifies a common non-extremal channel (e.g., depolarizing channel).
  - **Key `toqito` Usage:** Generating a Choi matrix for a depolarizing channel using `toqito.channels.depolarizing`, and applying `toqito.channel_props.is_extremal`.
  - **Value:** Provides essential contrast, reinforces user understanding of channel properties and the mathematical basis for extremality, connects `channels` module usage to `channel_props`.

Stretch Goals (Potential Additional Examples if Time Permits)

To ensure the core deliverables are completed to a high standard (including implementation, documentation, testing, and review) within the 225-hour timeframe, the following examples are designated as stretch goals. They will be pursued if the core set is completed ahead of schedule:

- **Stretch Example A: Illustrating a Sufficient Condition via Inner Product Bounds**
  - Based on Corollary 5.4 from arXiv:2311.17047 , demonstrating the practical SDP-free check. Uses `matrix_ops` and `state_opt.state_exclusion`.
- **Stretch Example B: Comparative Analysis of Channel Properties**
  - Comparing `is_extremal`, `is_unitary`, and `is_unital` across various channel types (Pauli, Depolarizing, Amplitude Damping). Uses `channel_props` functions extensively.

7. Preliminary Project Timeline (Based on 225 hours / 12 weeks)

- **Community Bonding Period (Approx. May):**
  - **Deepen understanding** of `toqito` modules relevant to the gallery examples and finalize familiarity with the documentation structure (e.g., Sphinx/Sphinx-Gallery integration points).
  - **Confirm and optimize** development environment for gallery generation and testing.

- **Finalize technical approach** for gallery infrastructure (e.g., confirm Sphinx-Gallery usage and strategy for tiled thumbnail layout).
- **Refine understanding** of core examples with mentors.
- **Continue active engagement** with the `toqito` community on Discord/GitHub, focusing on project planning.

- **Week 1-2:**
  - Focus heavily on **configuring and implementing the core gallery infrastructure** using (confirmed tool, e.g., Sphinx-Gallery) to achieve the target tiled thumbnail layout within the `toqito` documentation.
  - Begin development and documentation of **Example 5 (Unitary Extremality)** once the basic gallery structure is functional.
  - Submit initial PR showcasing the gallery structure (even if basic) and potentially partial/complete Example 5 for early feedback.
  - **Goal:** Functional gallery page structure rendering correctly within docs, initial example draft available, feedback sought on structure implementation.
- **Week 3-4:**
  - Complete development and documentation for **Example 5 (Unitary Extremality)**.
  - Develop and document **Example 6 (Non-Extremal Channels)**.
  - Incorporate feedback on the gallery structure PR. Submit PR for Example 5.
  - **Goal:** Gallery structure refined based on feedback. Example 5 complete and under review. Example 6 coded.
- **Week 5-6:**
  - Complete development and documentation for **Example 6**.
  - Begin work on **Example 1 (BC Hiding Failure via ENLG)** - start tackling ENLG customization.
  - Submit PR for Example 6. Continue review process for gallery structure and Example 5.
  - **Goal:** Channel props examples (5 & 6) complete and under review/merged. First ENLG example (1) started.
- **Week 7-8 (Includes Mid-term Evaluation):**
  - Complete development and documentation for **Example 1**.
  - Begin work on **Example 2 (QKD QBER Bounds via ENLG)**.
  - Focus on addressing review feedback for gallery structure, Examples 5, 6, & 1, aiming for merges.
  - **Mid-term Evaluation:** Ensure gallery structure and several examples (aim for 2-3) are coded, documented, tested, reviewed, and ideally at least one major PR (structure or an example) is merged or close to merging.
  - **Goal:** Gallery structure stable/merged. ENLG Example 1 complete/under review. ENLG Example 2 started. Positive mid-term evaluation status.
- **Week 9-10:**
  - Complete development and documentation for **Example 2**.

  - Develop and document **Example 3 (Antidistinguishability Threshold)** - requires understanding literature/state_opt.
  - Submit PRs for Examples 1 & 2. Continue review/merge process for all completed items.
  - **Goal:** Both ENLG examples complete and under review/merged. First state_opt example (3) coded.

- **Week 11-12:**
  - Complete development and documentation for **Example 3**.
  - Develop and document **Example 4 (Circulant State Antidistinguishability)** - involves `rand` and eigenvalue analysis.
  - Finalize documentation, testing, and address any remaining review feedback for *all* 6 core examples and the gallery structure. Ensure the gallery page is polished and integrates well.
  - **Crucial:** Ensure at least one significant PR (ideally containing several examples or the final gallery structure) is fully **merged** into `toqito`'s main branch to meet the GSoC final requirement.
  - Submit PRs for Examples 3 & 4.
  - **If time permits:** Begin working on **Stretch Example A or B**, submitting as separate PRs.
  - Prepare final submission and project summary/report.
  - **Goal:** All 6 core examples completed, reviewed, and integrated into a functional gallery. Merge requirement met. Stretch goals attempted if feasible. Final report ready.

- **Throughout:** Bi-weekly blog posts documenting progress, challenges, and learnings. Daily communication with mentors. Frequent commits to public repository.