Quantum Software Development Lifecycle

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Tutorial Structure

- Session 1 (09:00 - 10:30): An Introduction to Quantum Computing

- **Session 2 (11:00 - 12:30): Quantum Software Engineering**
  - Quantum software development lifecycle
  - Quantum hardware selection
  - Q/A session
  - Outlook to the afternoon sessions

- Session 3 (14:00 - 15:30): Quantum Workflows

- Session 4 (16:00 - 17:30): Operation of Hybrid Quantum Applications

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Motivation

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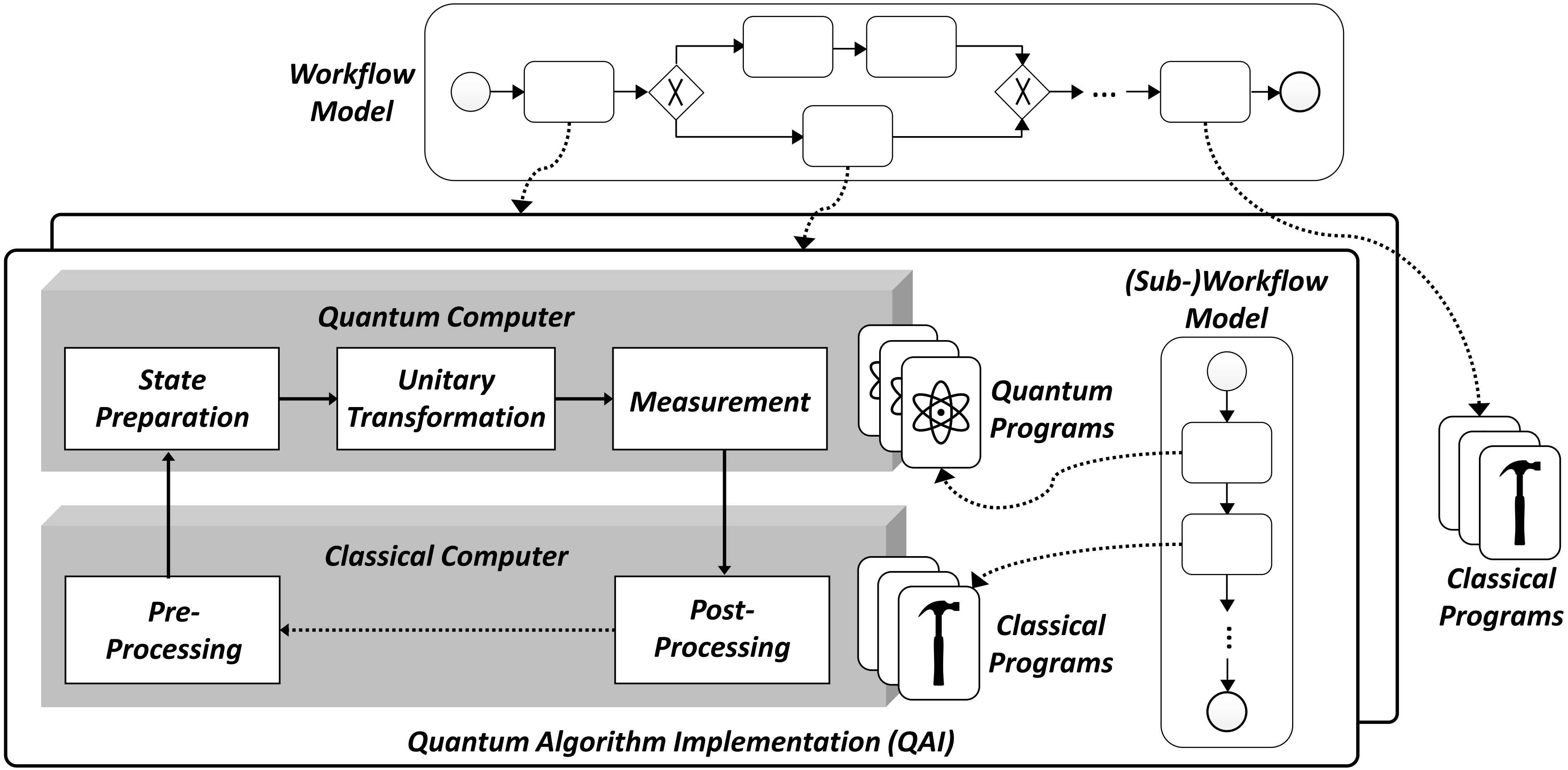
- Recent advances with more powerful quantum computers
  → New quantum applications are needed

- Development of quantum applications requires expertise from different fields:
  - Computer science
  - Physics
  - Mathematics
  - …

- Common understanding of the development and execution process needed

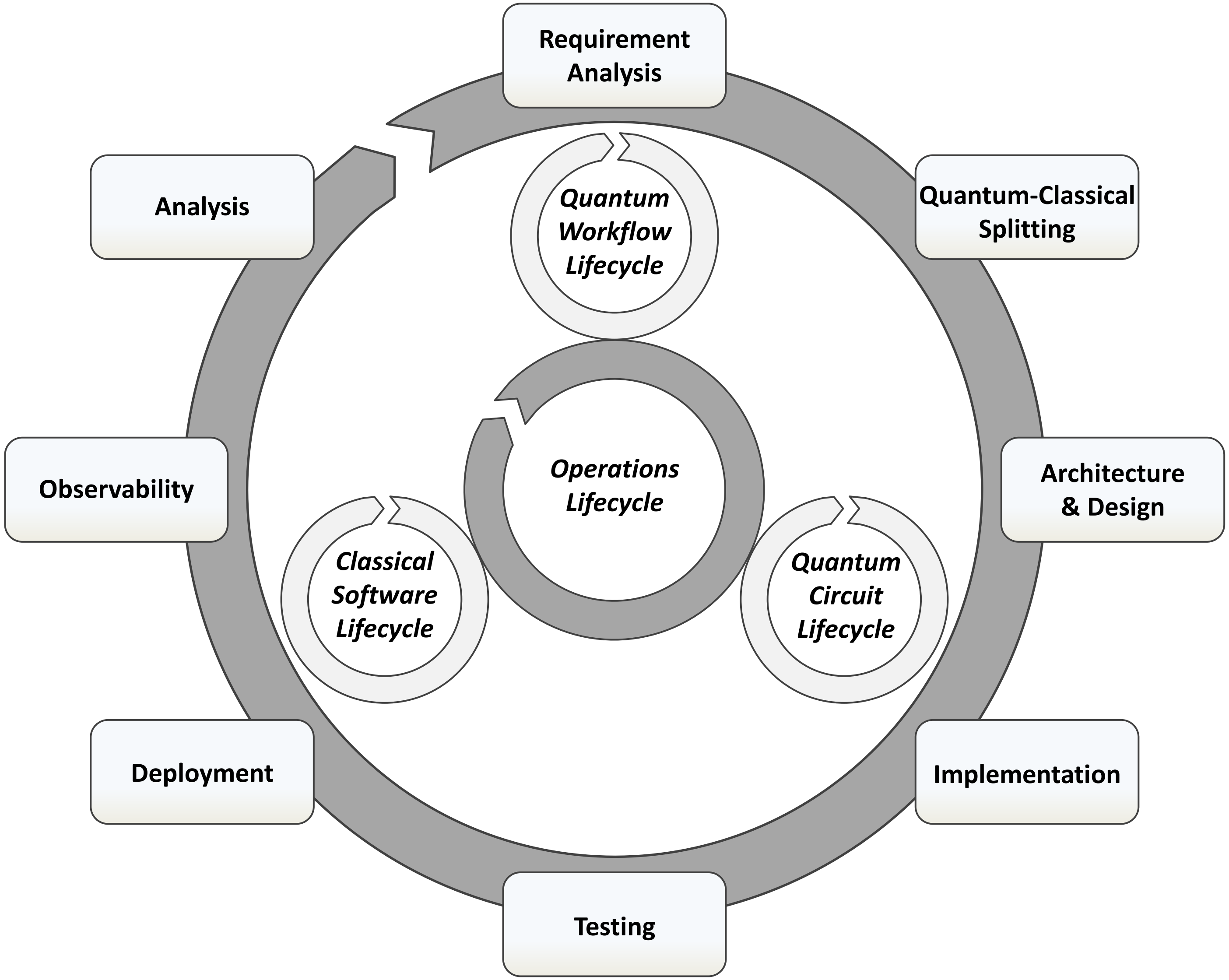
→ *Quantum Software Development Lifecycle*

Structure of a Hybrid Quantum Application

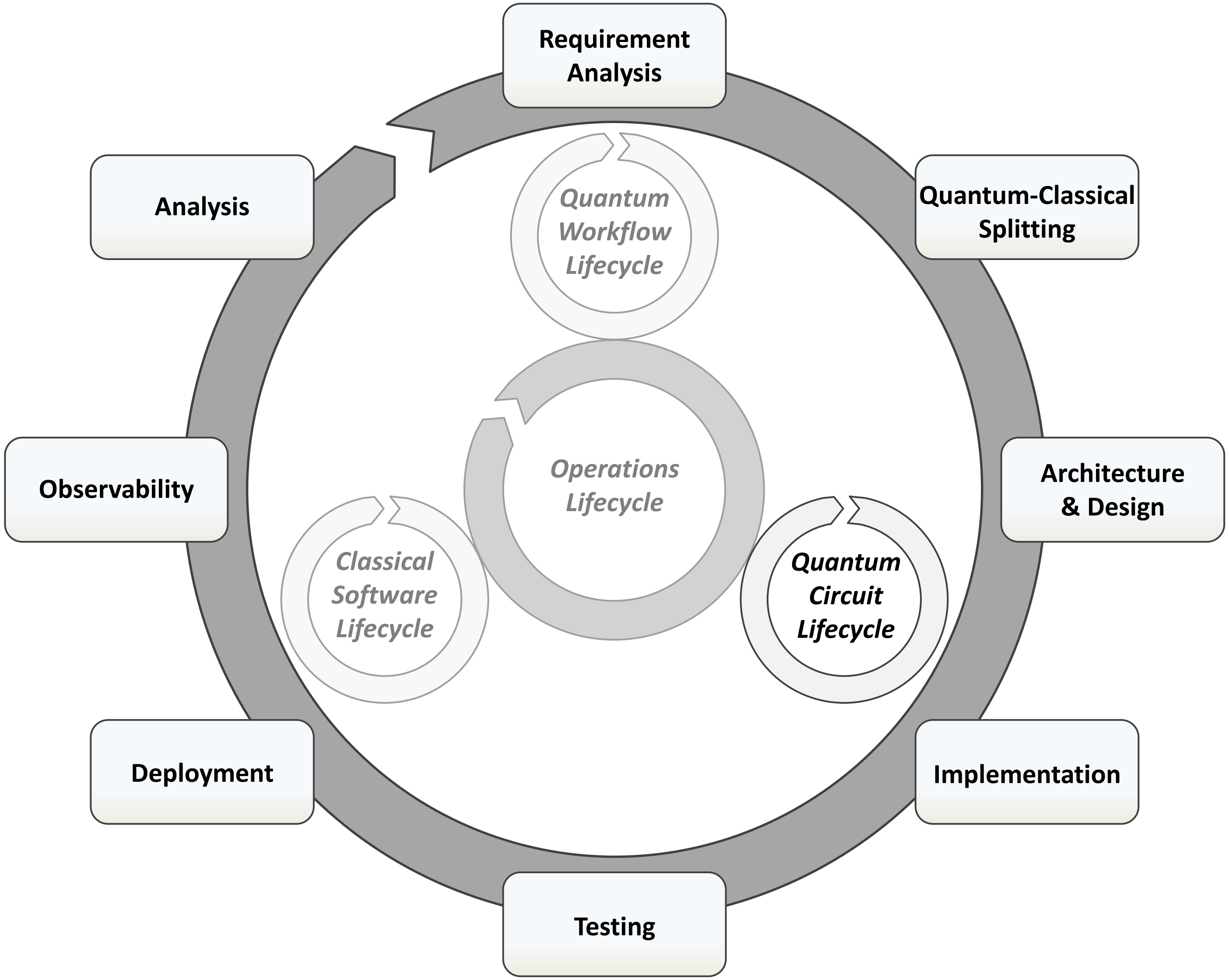


Quantum Software Development Lifecycle

Quantum Software Lifecycle – Interwoven Lifecycle



Focus of this Session



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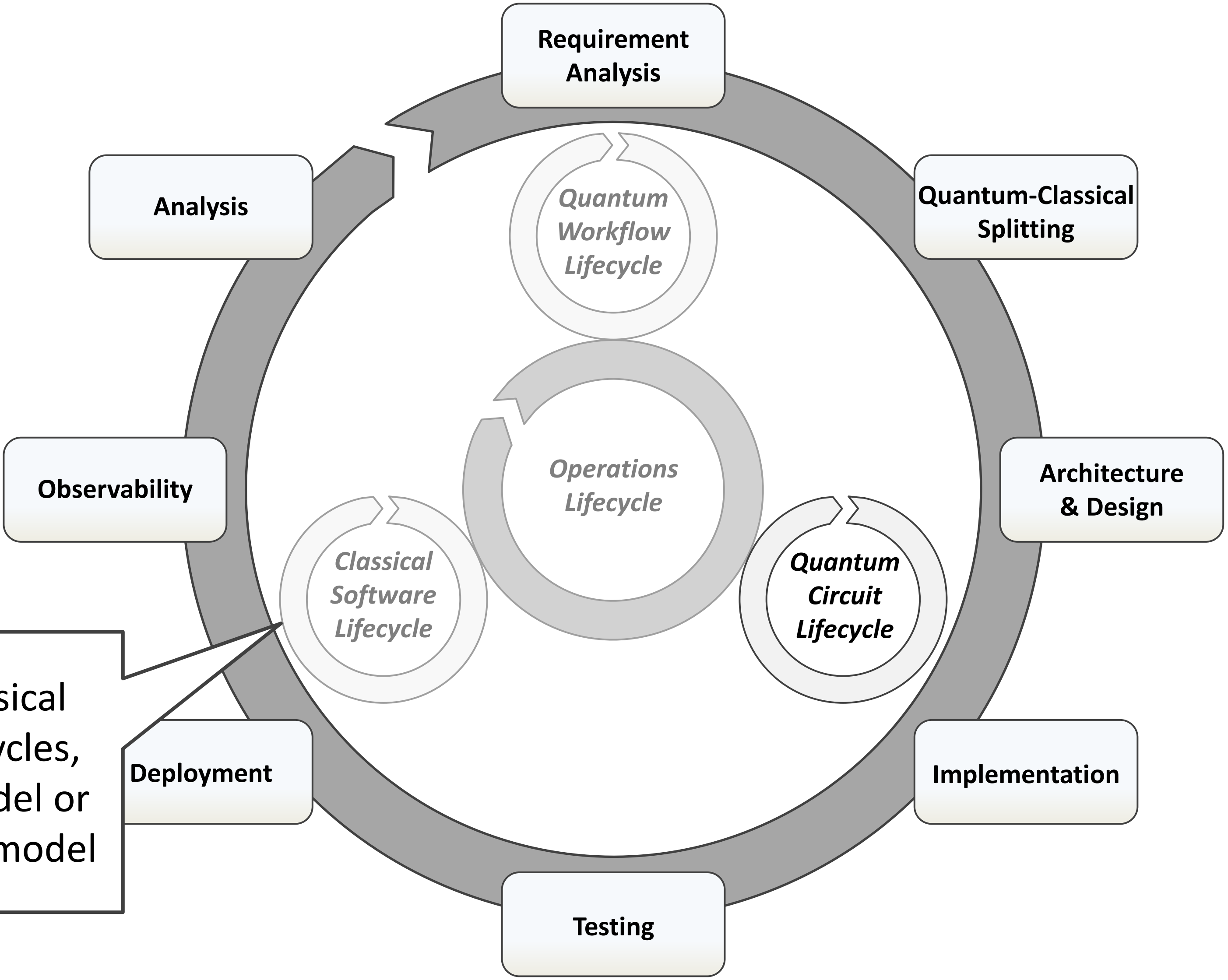

Usage of classical software lifecycles, e.g., the V-model or the prototype model

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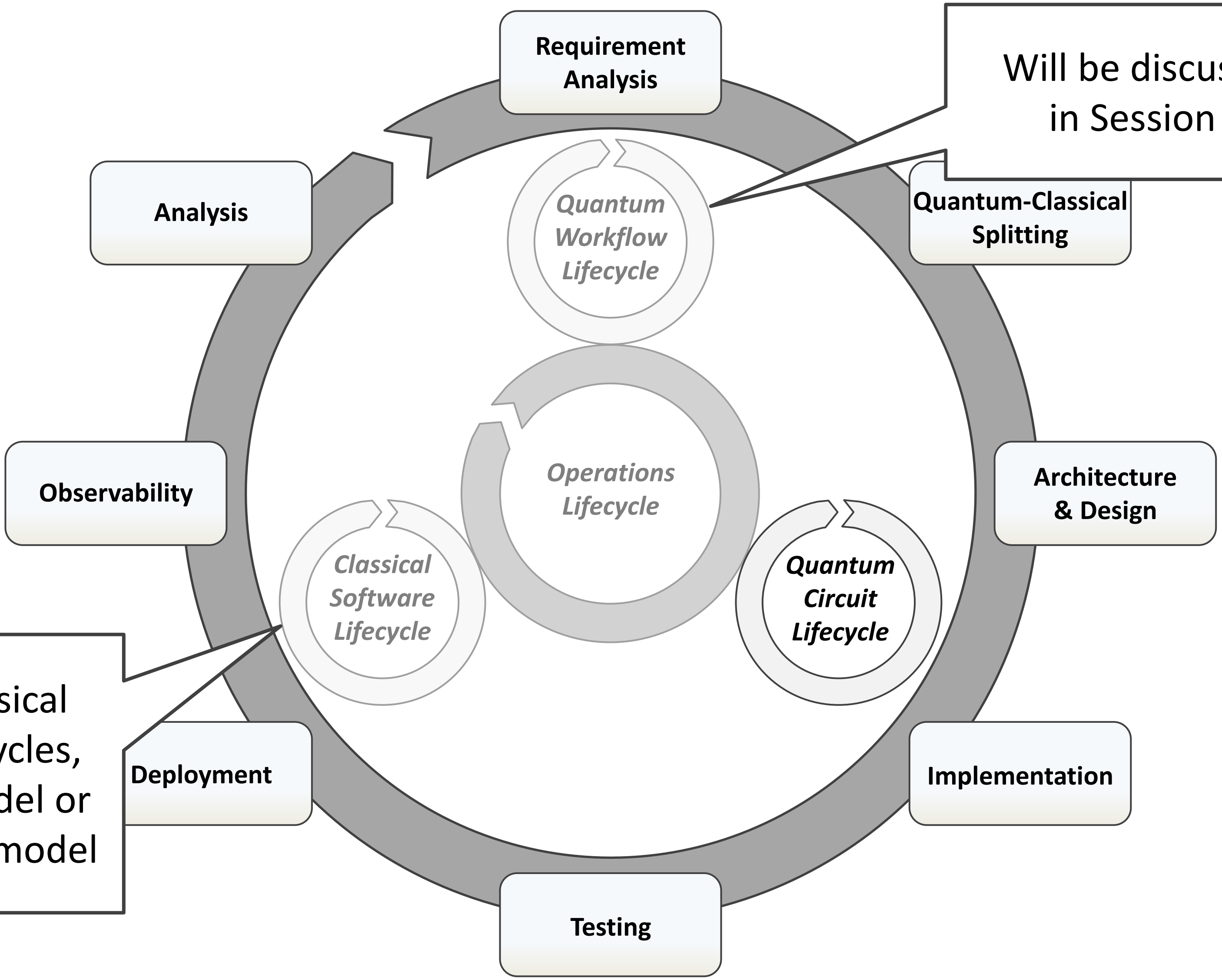

Will be discussed in Session 3

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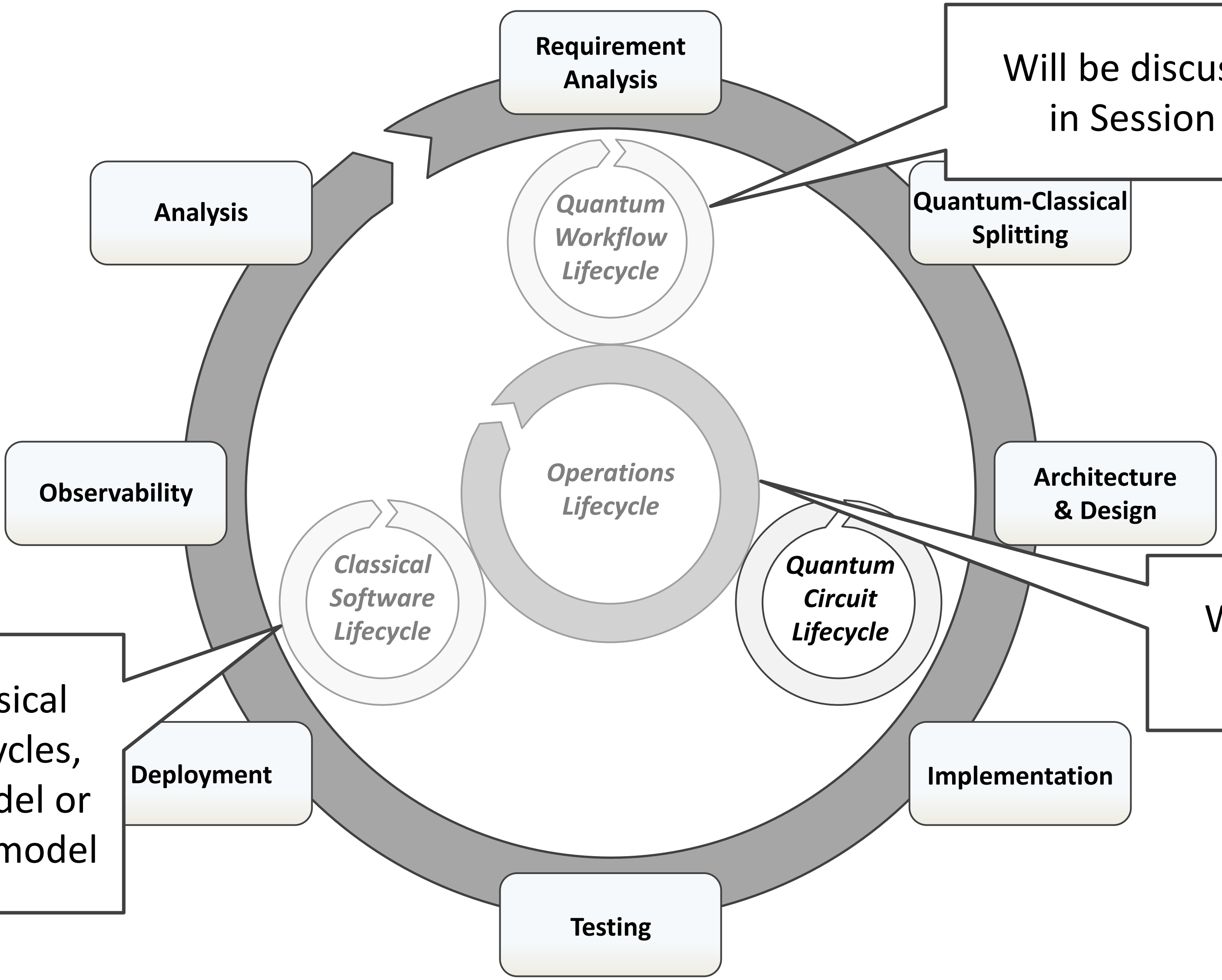

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Usage of classical software lifecycles, e.g., the V-model or the prototype model

Enclosing Lifecycle

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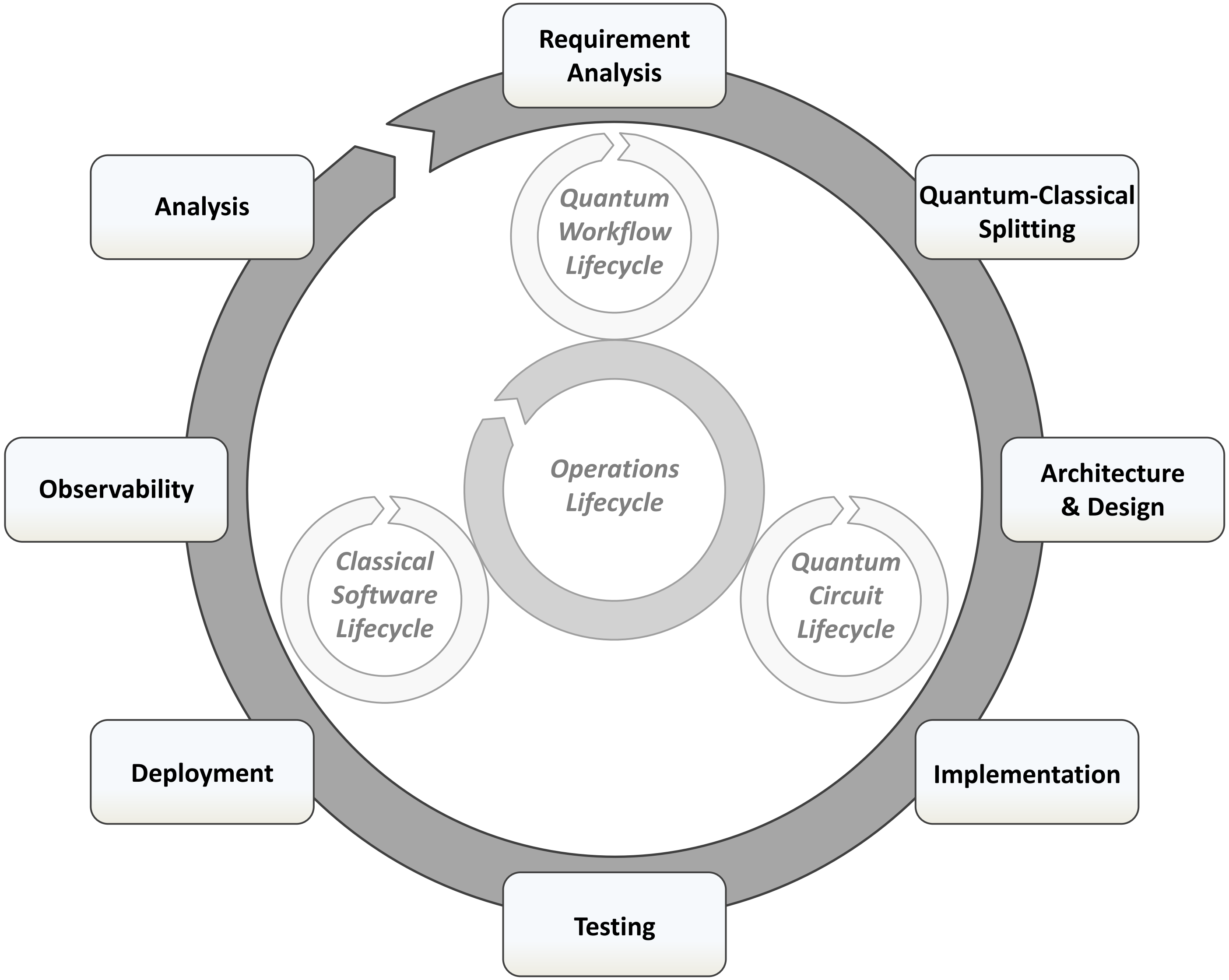

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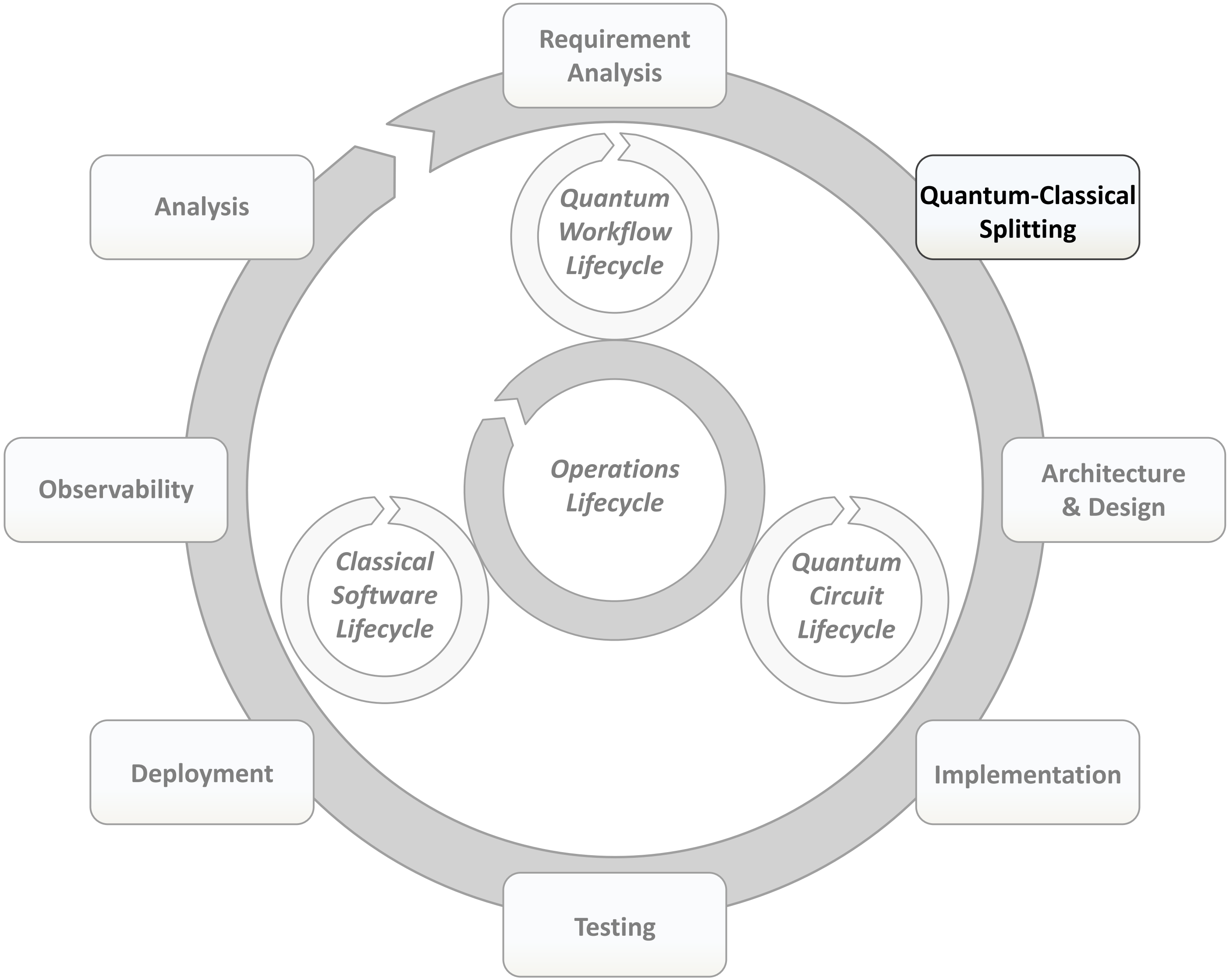
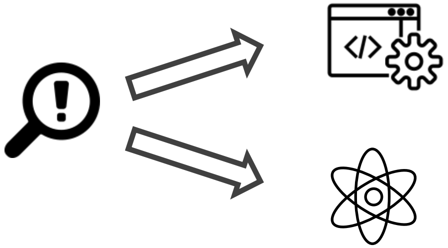


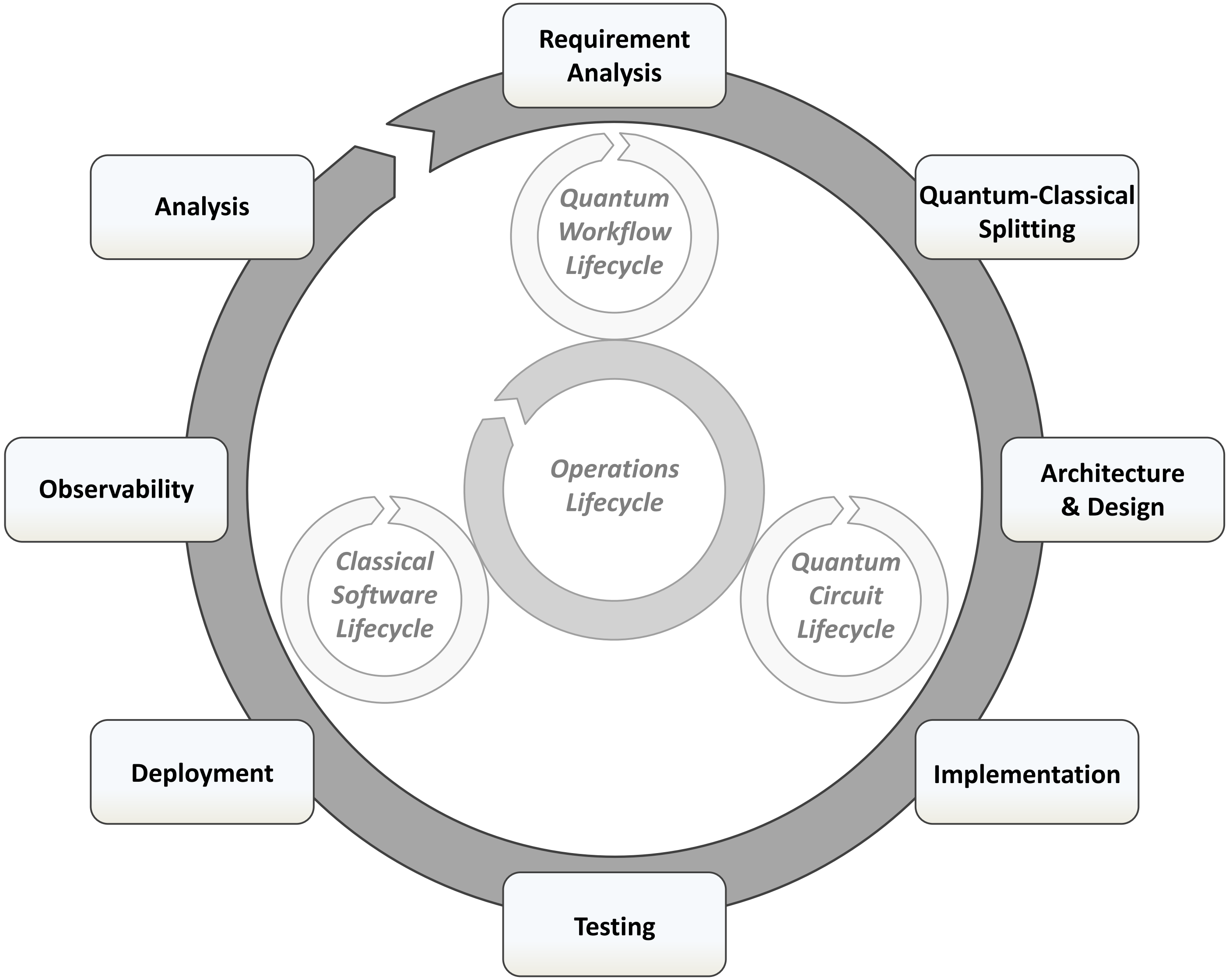
Quantum-Classical Splitting

- Entered by the user with the identified requirements
- Split problem to solve into quantum and classical parts:



- Different techniques:
  - Manually by experts
  - Comparison of quantum algorithms with classical algorithms ➔ QHAna
  - Automated recommender (based on patterns, provenance, …)

Enclosing Lifecycle



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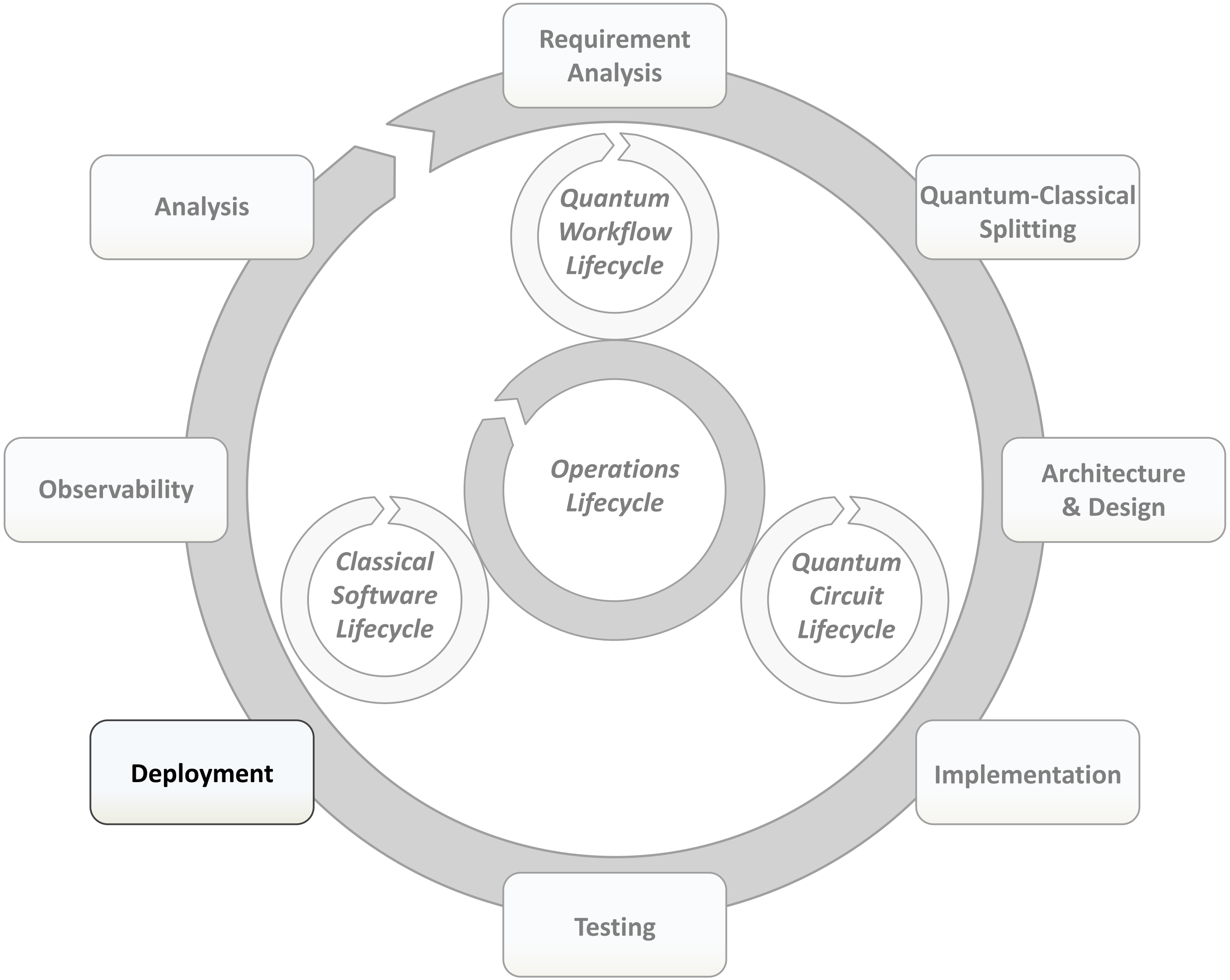
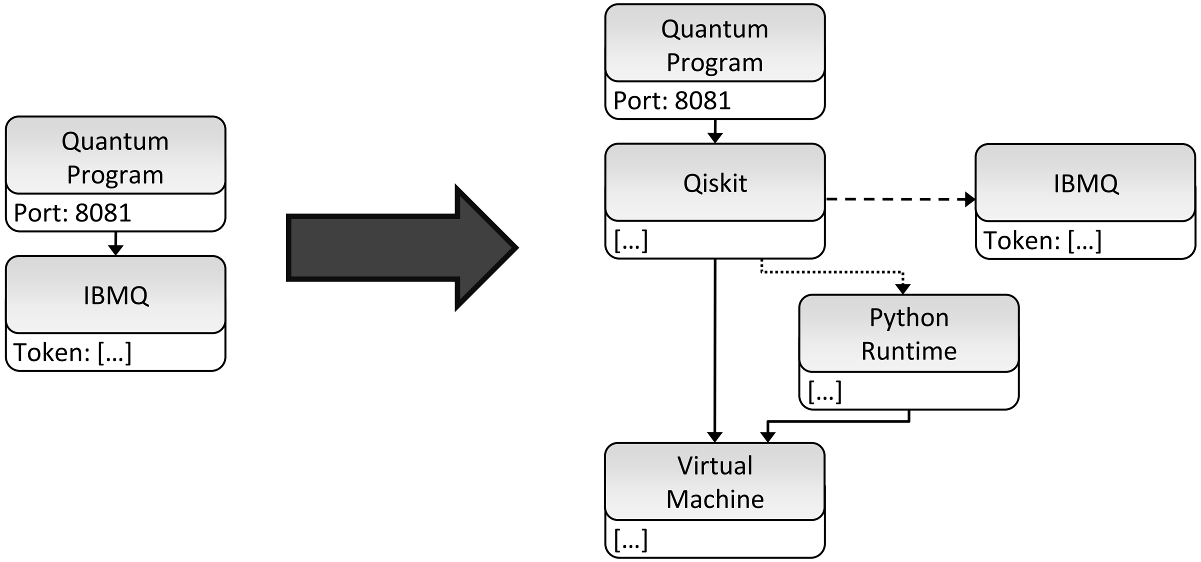


Topology Modeling – TOSCA4QC

- Quantum programs are often deployed when they are invoked
- Common modeling principles do not apply
- *TOSCA4QC*:
  - Introcude two modeling styles for quantum applications
  - Automatic transformation between them



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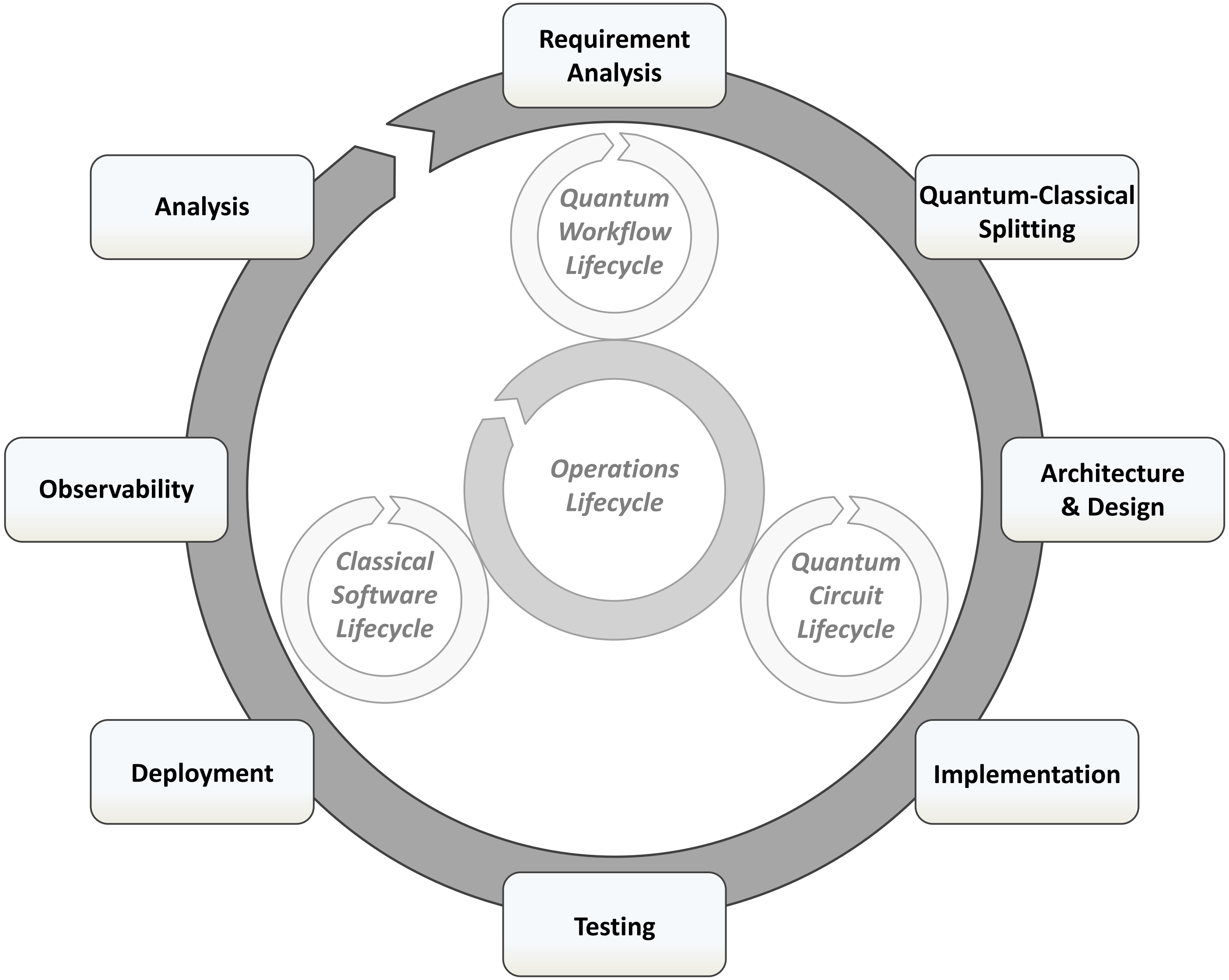

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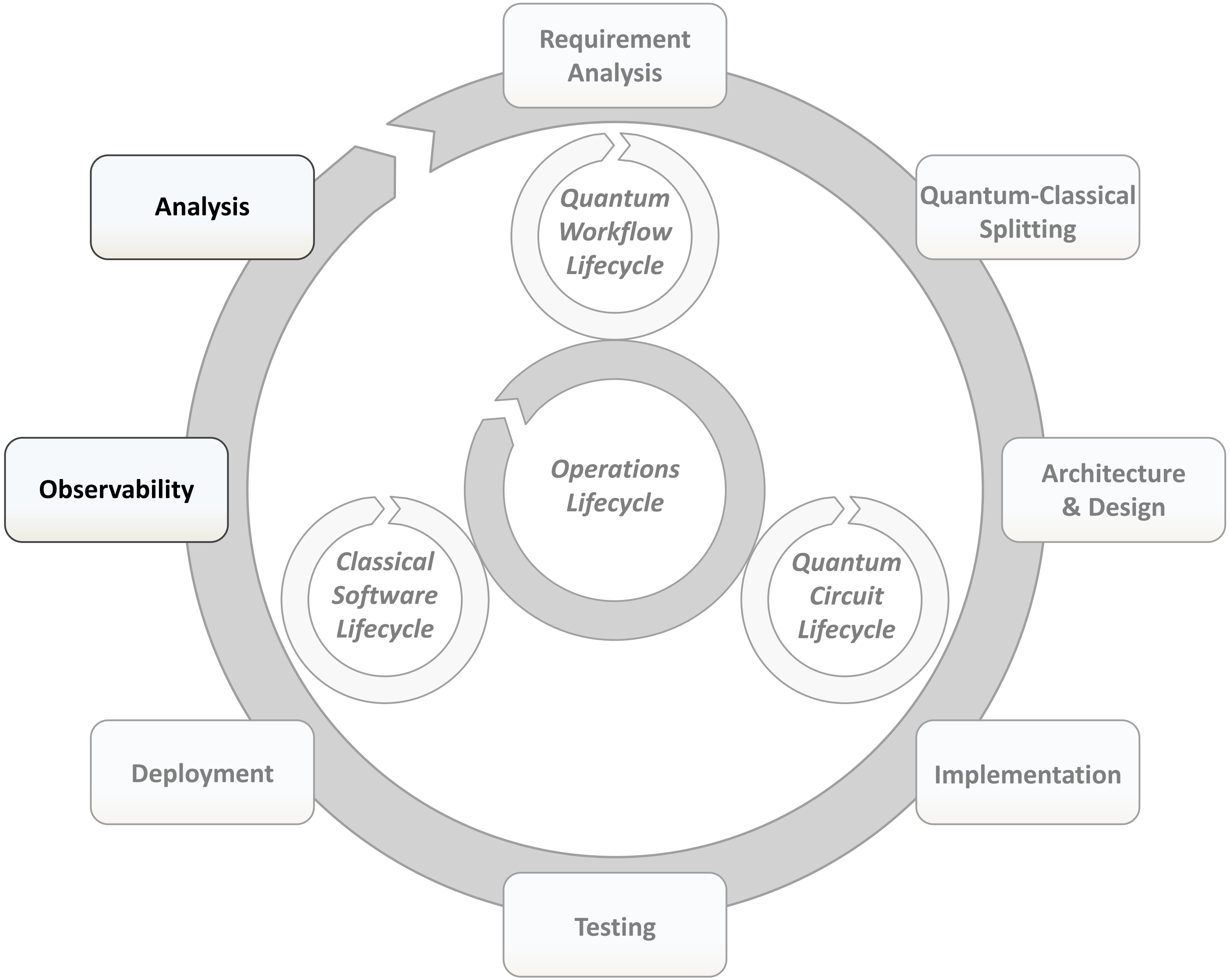


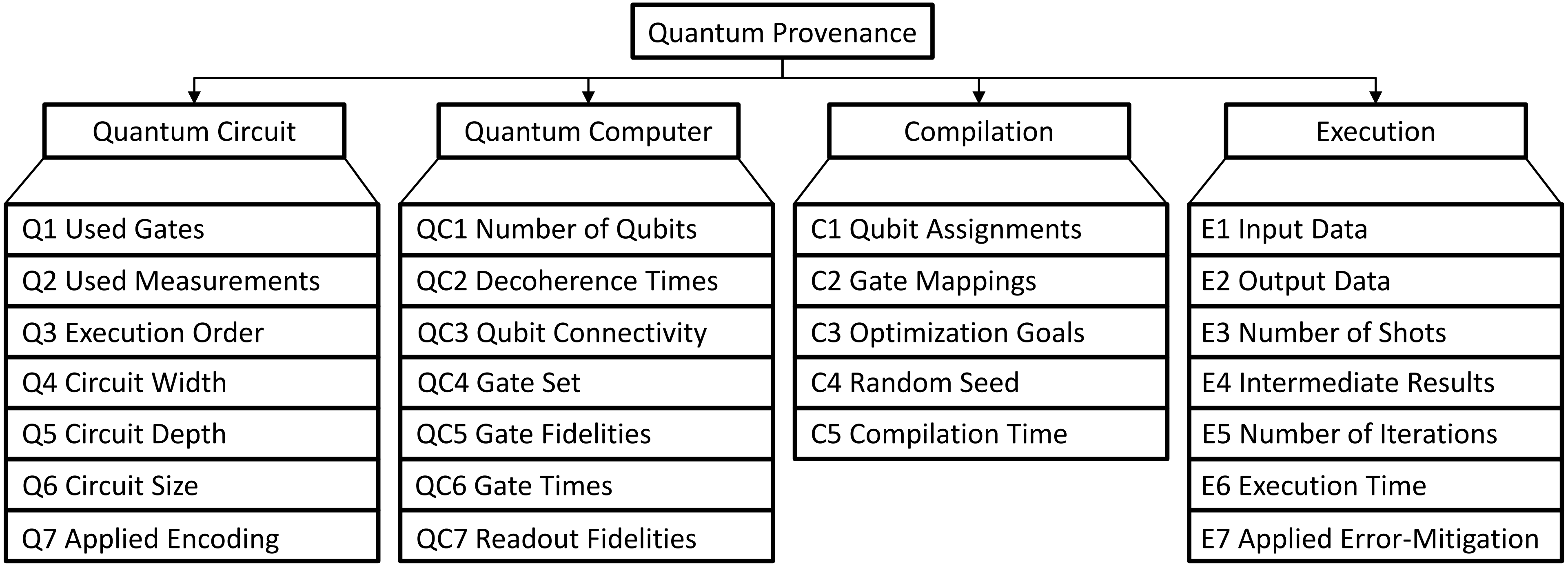
Quantum Provenance

- Provenance
  - Information describing a process or computation
  - Goals: reproducibility, understandability, quality

- Especially important for quantum computing
  - Noisy devices (decoherence, gate errors, …)
  - Different realizations (trapped ions, superconducting, …)

- Example use cases:
  - Quantum hardware selection
  - Readout-error mitigation
  - Optimization & compilation

Quantum Provenance Attributes

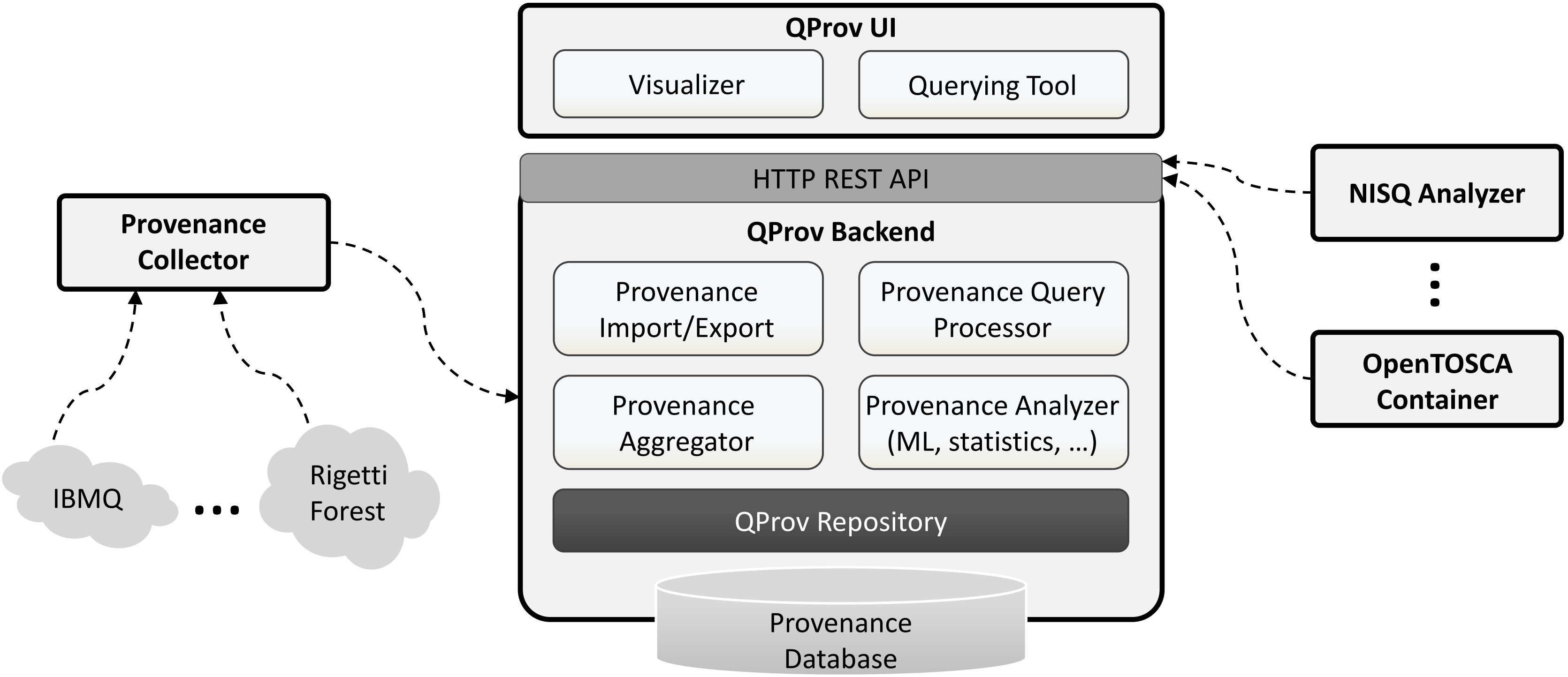


Quantum Provenance

Quantum Circuit	Quantum Computer	Compilation	Execution
Q1 Used Gates	QC1 Number of Qubits	C1 Qubit Assignments	E1 Input Data
Q2 Used Measurements	QC2 Decoherence Times	C2 Gate Mappings	E2 Output Data
Q3 Execution Order	QC3 Qubit Connectivity	C3 Optimization Goals	E3 Number of Shots
Q4 Circuit Width	QC4 Gate Set	C4 Random Seed	E4 Intermediate Results
Q5 Circuit Depth	QC5 Gate Fidelities	C5 Compilation Time	E5 Number of Iterations
Q6 Circuit Size	QC6 Gate Times		E6 Execution Time
Q7 Applied Encoding	QC7 Readout Fidelities		E7 Applied Error-Mitigation

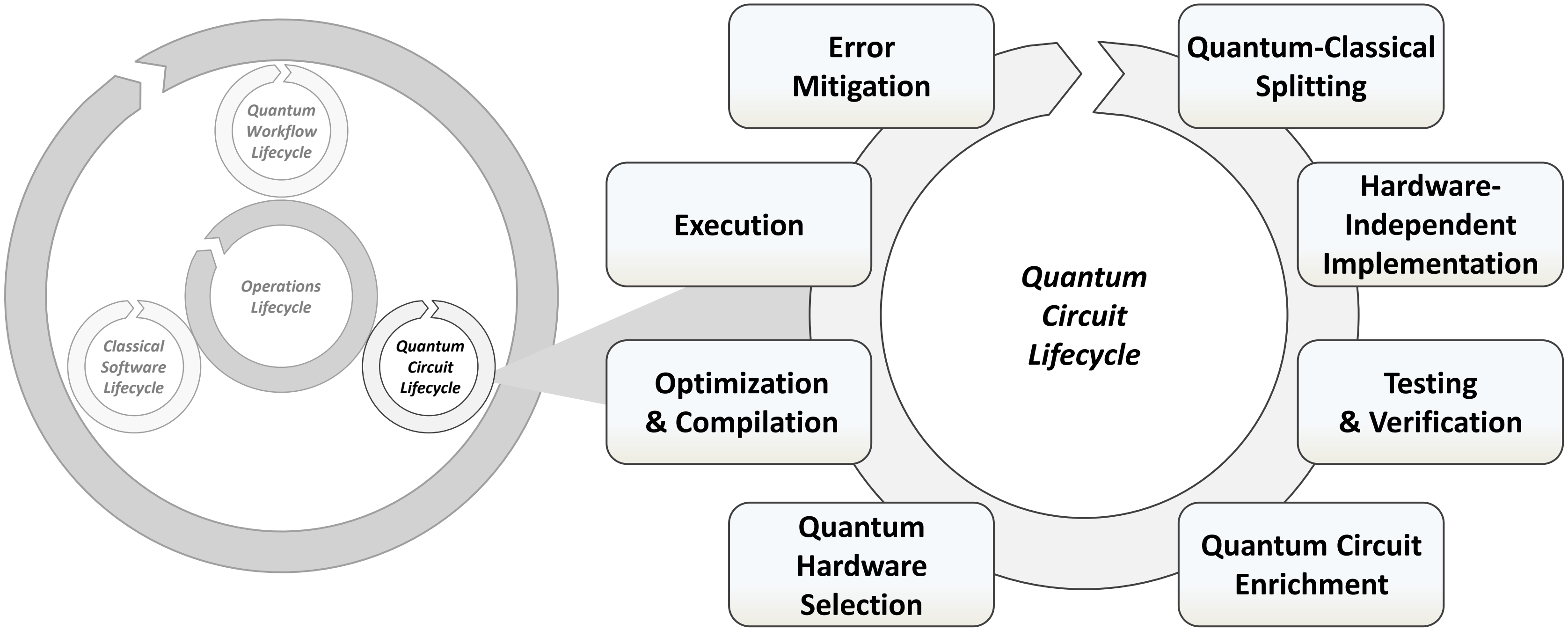
The QProv System

- Quantum provenance framework:
  - Continuously gather all required data
  - E.g., through the provider API, by executing calibration circuits, …



Quantum Circuit Lifecycle

Detailed View of the Quantum Circuit Lifecycle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Operations Lifecycle
Classical Software Lifecycle
Quantum Circuit Lifecycle
Error Mitigation
Quantum-Classical Splitting
Execution
Hardware-Independent Implementation
Quantum Circuit Lifecycle
Optimization & Compilation
Testing & Verification
Quantum Hardware Selection
Quantum Circuit Enrichment

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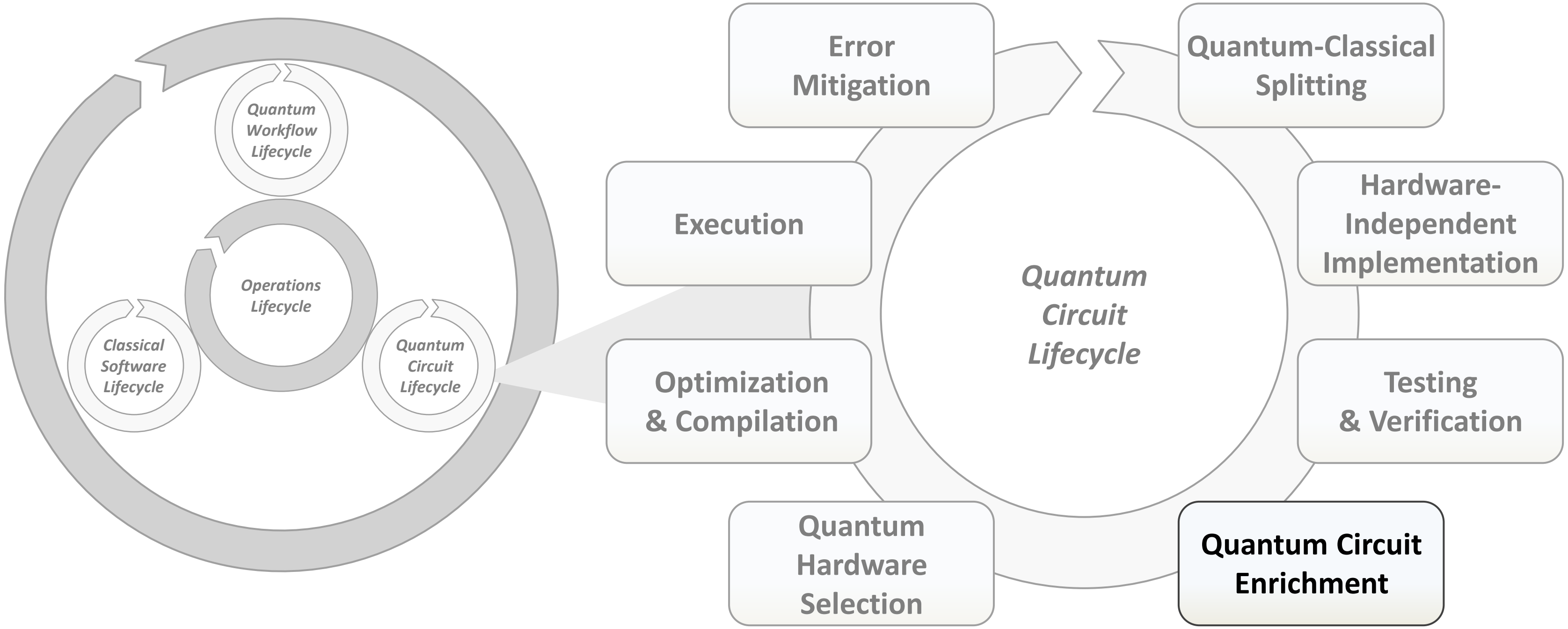
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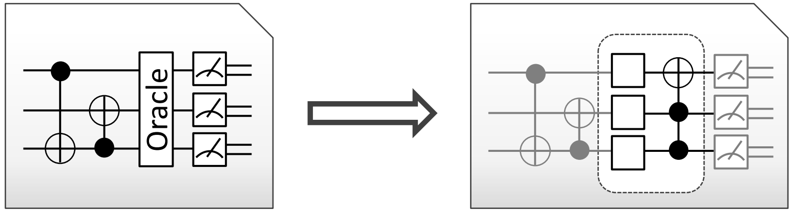
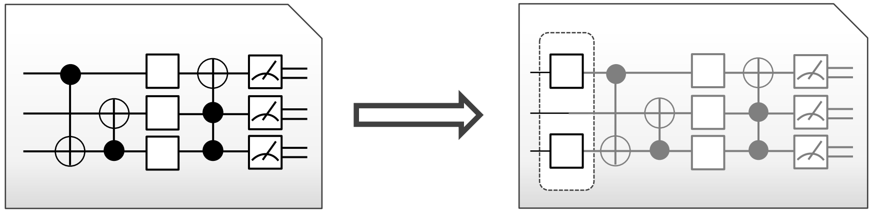
Quantum Circuit Enrichment

- Enrichment with details for a certain problem instance

- Oracle expansion:



- Data preparation:
  - Adding an initialization circuit to the beginning of the original circuit
  - Different encodings: basis encoding, angle encoding, …



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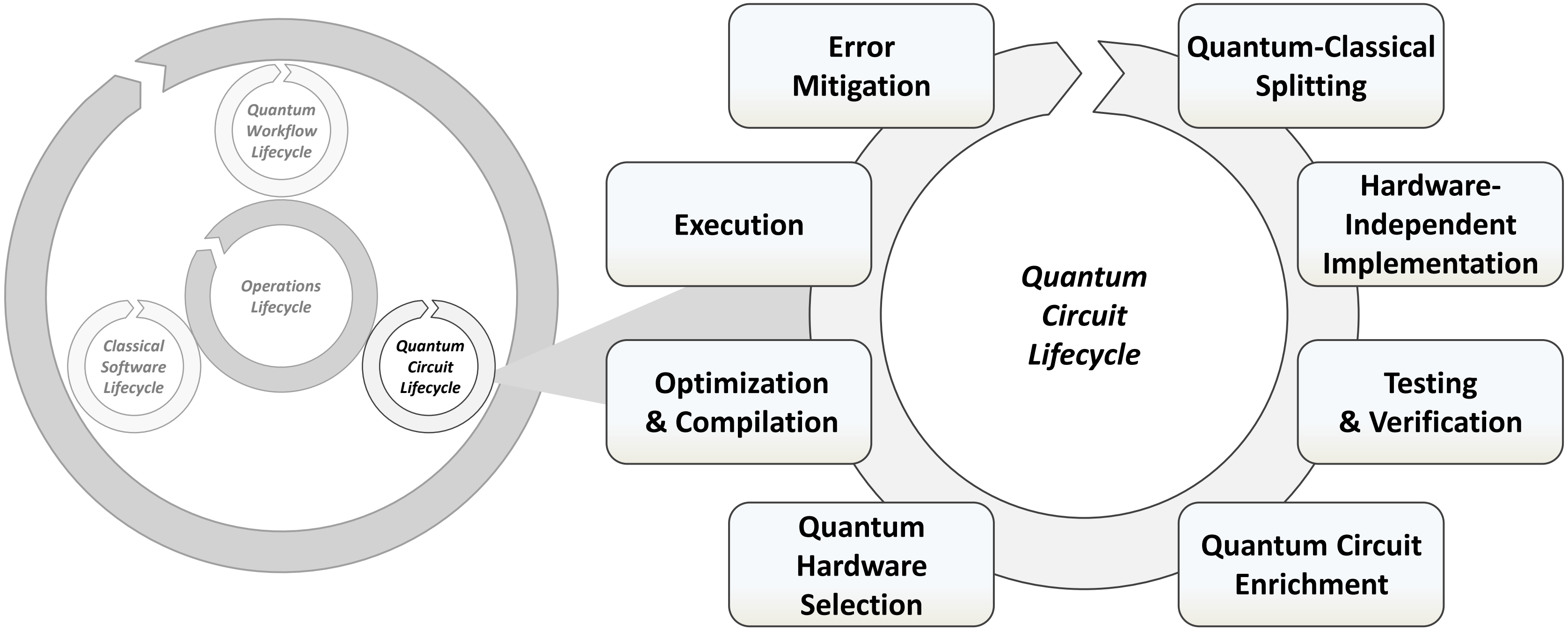
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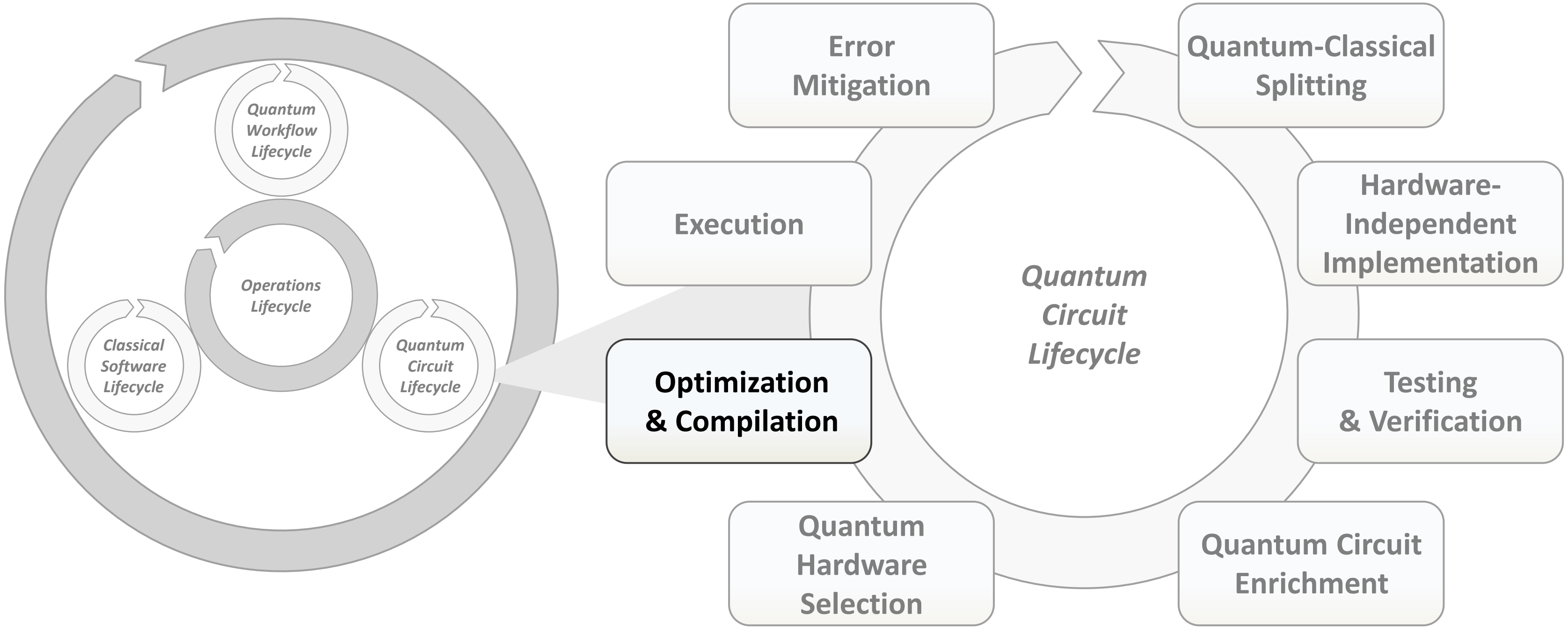
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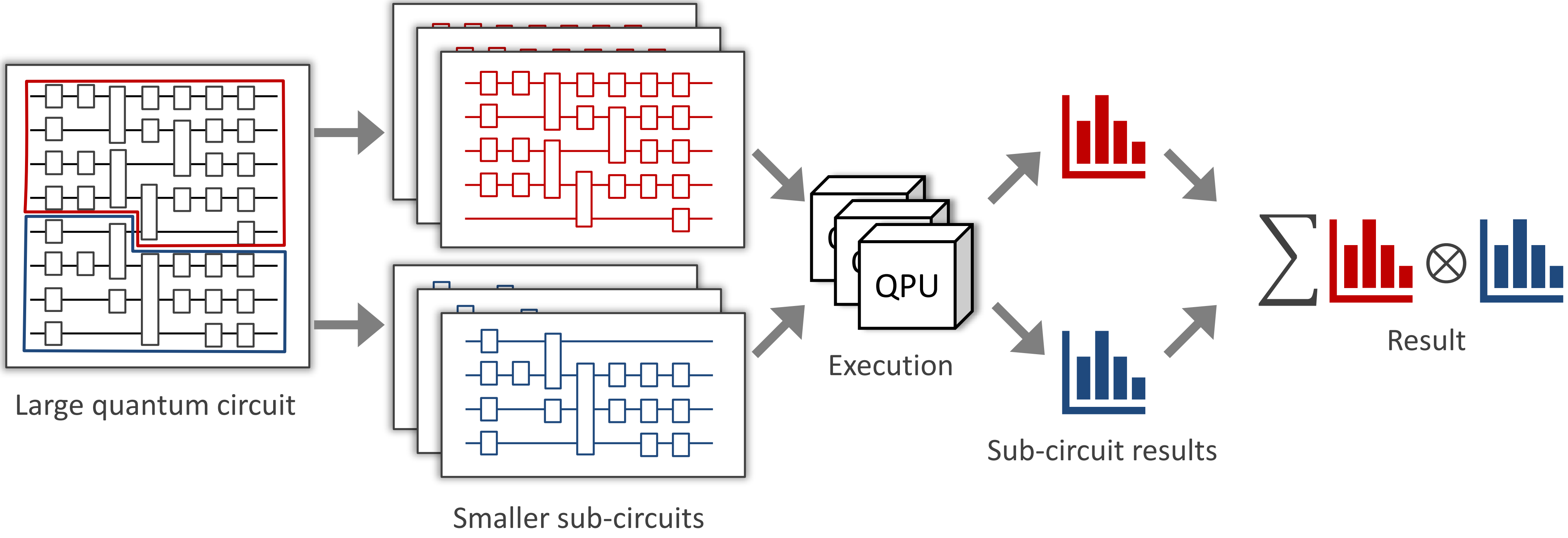
Optimization: Cutting Quantum Circuits

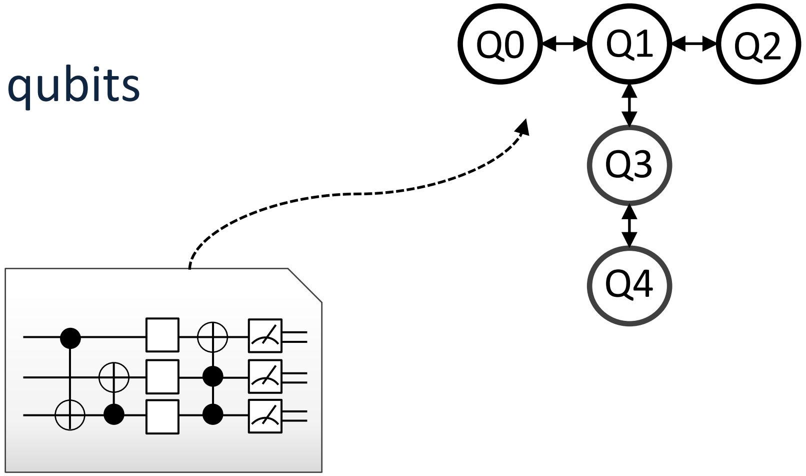
- Quantum circuits might be too large (width, depth) to retrieve good results
- Execute multiple smaller circuits
  ➔ Classical post-processing to combine results



Compilation of Quantum Circuits

- Compilation to machine instructions required
- Replacement of not physically implemented gates
- Qubit allocation on the quantum computer
- Optimization based on:
  - Decoherence times of different qubits
  - Gate fidelities
  - Qubit connectivity

ibmq_valencia topology



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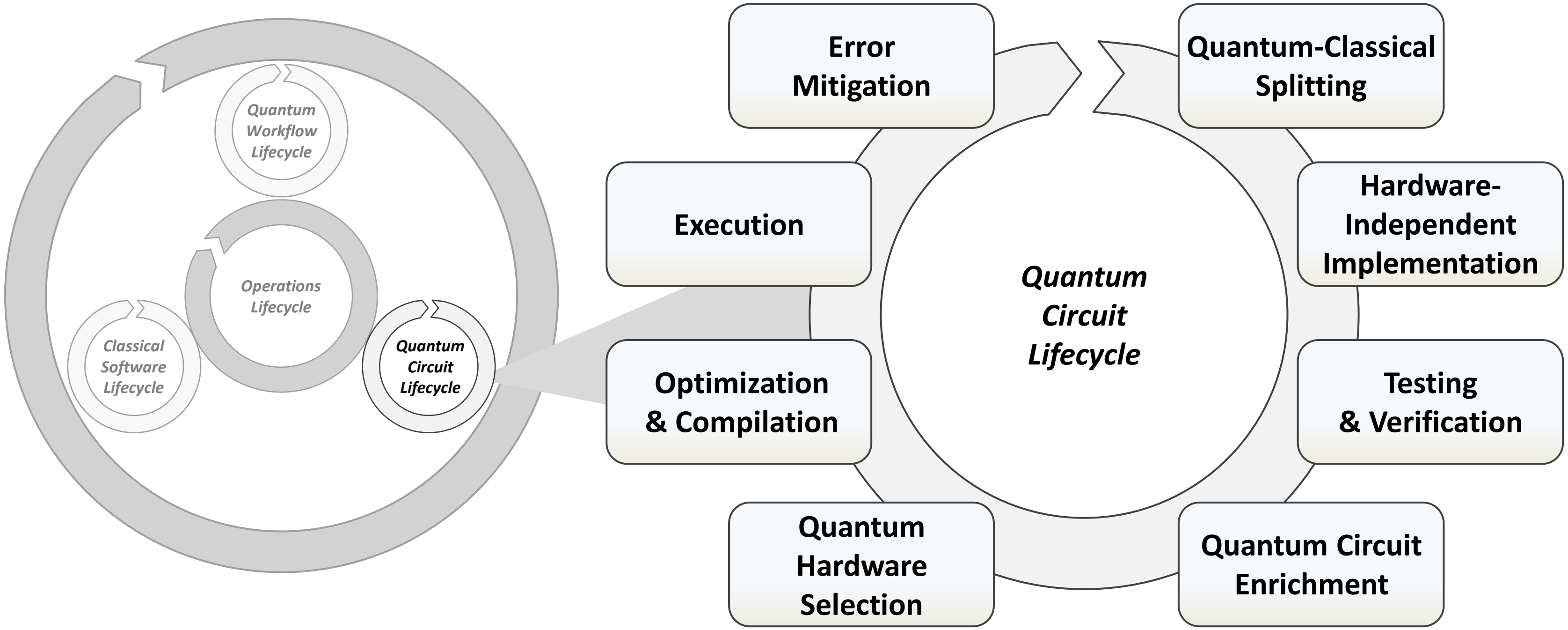
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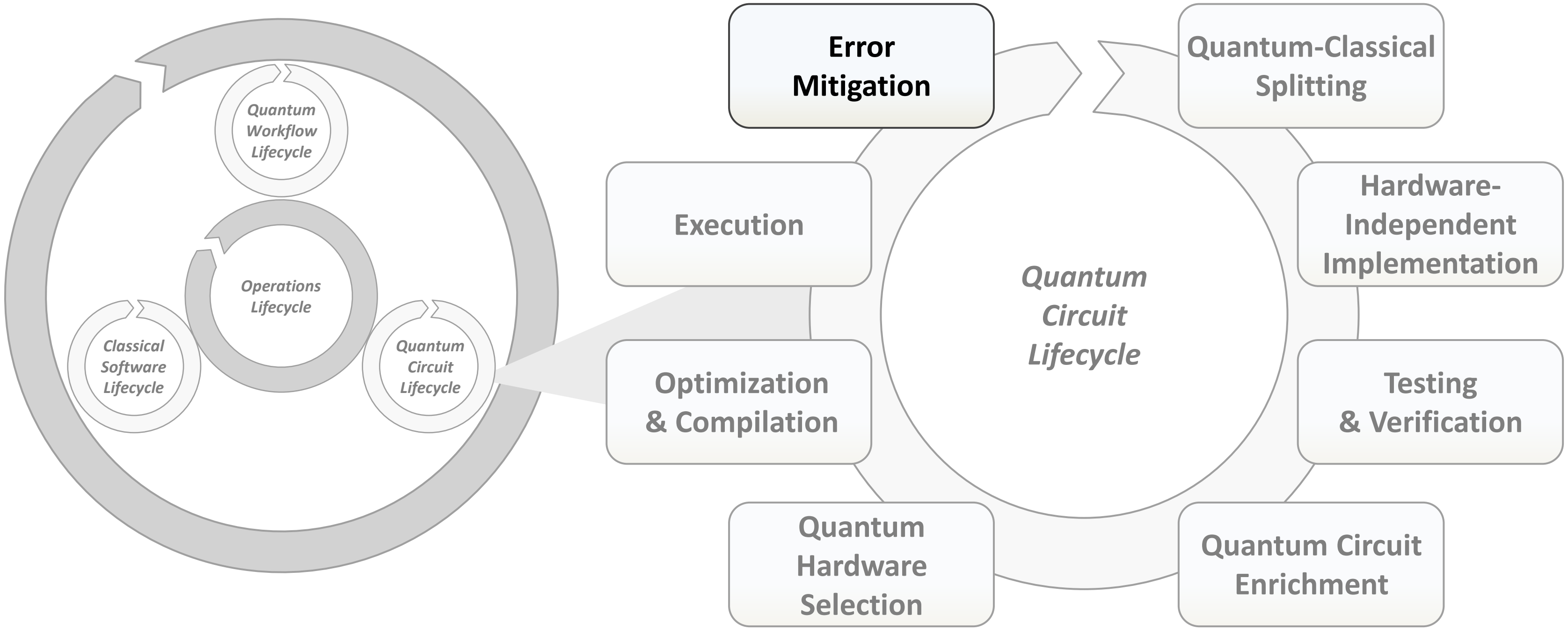
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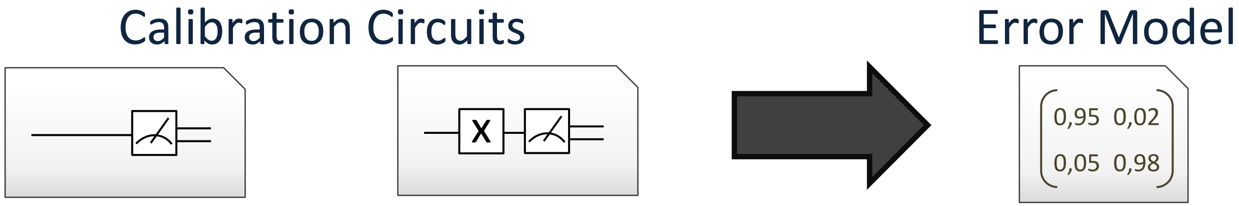
Error-Mitigation

- Reduce impact of errors based on data about the quantum computer
- Example: Readout-error mitigation using the calibration matrix
  - Data collection:

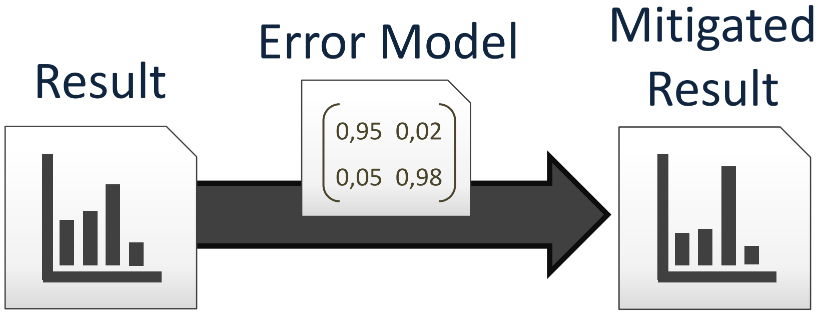


Calibration Circuits

Error Model

$$\begin{pmatrix} 0{,}95 & 0{,}02 \\ 0{,}05 & 0{,}98 \end{pmatrix}$$

  - Mitigating the result:



Result

Error Model

$$\begin{pmatrix} 0{,}95 & 0{,}02 \\ 0{,}05 & 0{,}98 \end{pmatrix}$$

Mitigated Result

Conclusion & Outlook

IAAS Research

Conclusion & Outlook

- Quantum application development is complex and requires experts from different fields
- Common understanding of the various phases and tasks is needed
- *Quantum Software Lifecycle*:
  - Interwoven lifecycles
  - Workflow, classical, quantum circuit, operations lifecycles
- Future work:
  - Many open problems, e.g., how to properly split a problem into quantum and classical parts?
  - Tooling support required (e.g., test, circuit cutting, …)

Thank you for your attention ☺