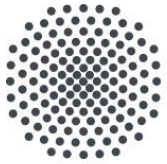
Quantum Workflows



University of Stuttgart

Martin Beisel, Benjamin Weder

{beisel,weder}@iaas.uni-stuttgart.de

UNIVERSIDAD de EXTREMADURA

Tutorial Structure

- **Session 1 (14:00 - 15:30): Quantum Service-oriented Computing**
  - Opening & Quantum Computing Fundamentals
  - Quantum Web Services
  - Practical Session: Quantum Web Services
  - Quantum Workflows
- Session 2 (16:00 - 17:00): Orchestrating Hybrid Quantum Applications
  - Practical Session: Quantum Workflows
  - Evaluation & Q/A

Tutorial Structure

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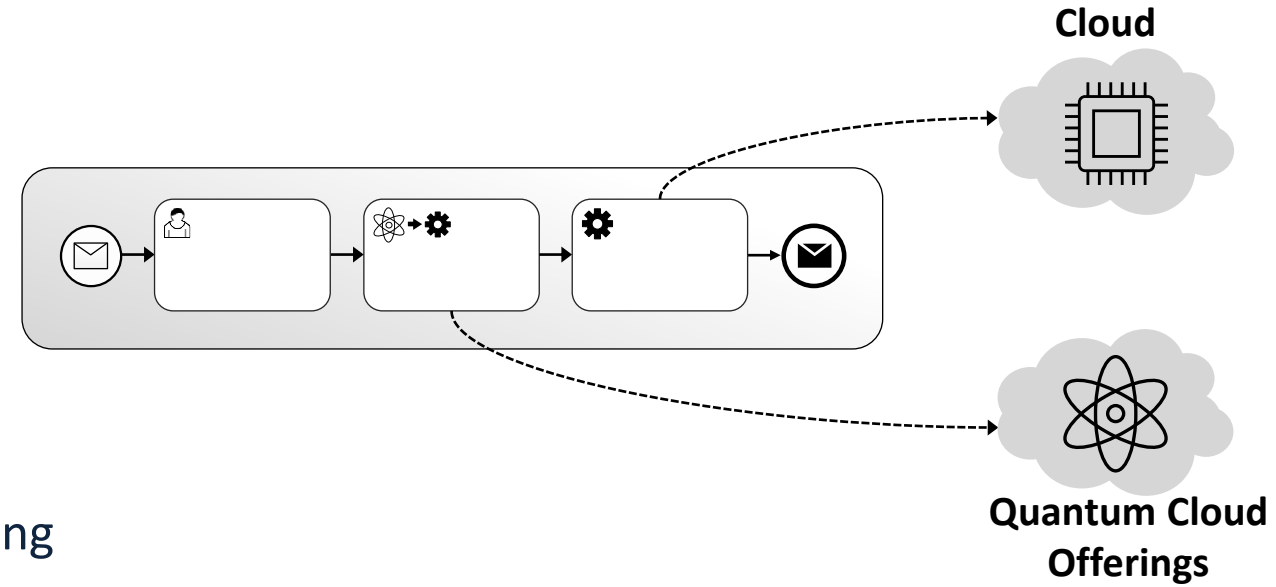
Motivation

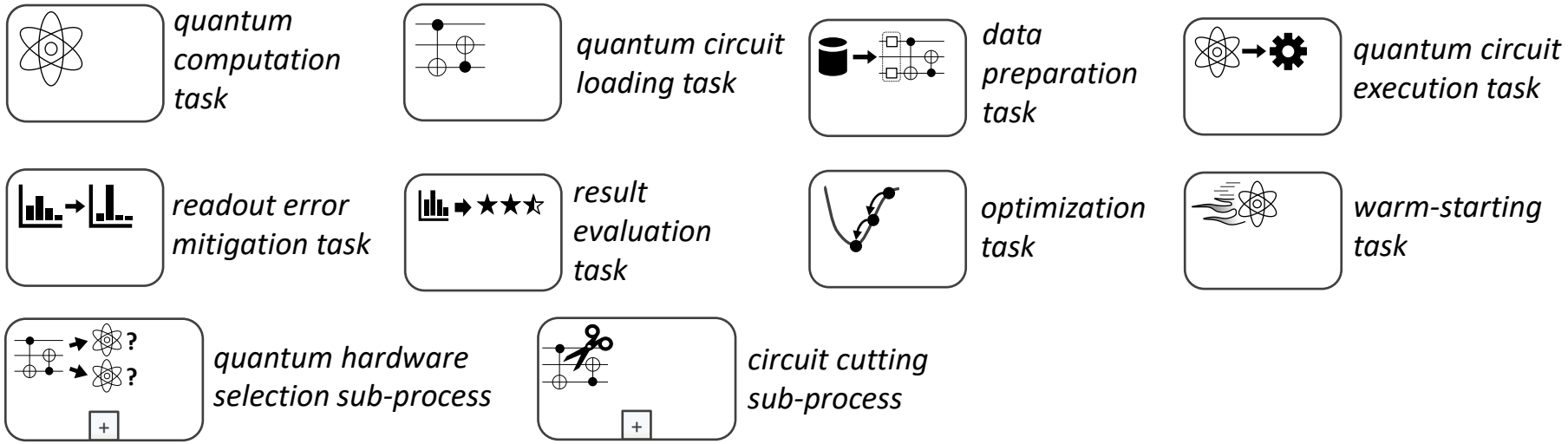
- Workflows enable orchestration and integration of heterogeneous applications
  - Definition of activities, control flow, and data flow

- Advantages:
  - Scalability
  - Robustness
  - Monitoring
  - Advanced Exception Handling
  - Portability via standardized languages (BPMN, BPEL)



Quantum Modeling Extension (QuantME)

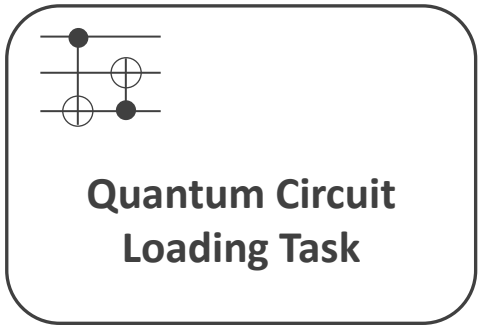
- Modeling extension for imperative workflow languages
- Facilitates the modeling of quantum applications
  - Quantum-specific modeling constructs

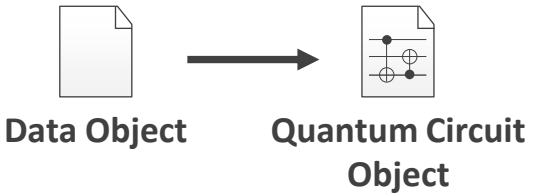


Quantum Circuit Loading Task

- Semantic:
  - Loading of a circuit of an executable quantum circuit
- Input and Output:
  - **Input:** Problem instance to solve
  - **Output:** Quantum Implementation as a Quantum Circuit Object
- Configuration attributes:
  - **Quantum Circuit**$^{\oplus}$**:** Source code of the quantum circuit
  - **URL**$^{\oplus}$**:** URL for loading or generating the quantum circuit

$^{\oplus}$ exclusive

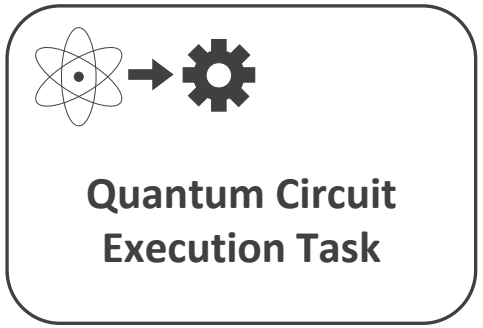


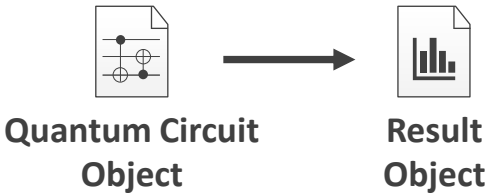


Quantum Circuit Execution Task

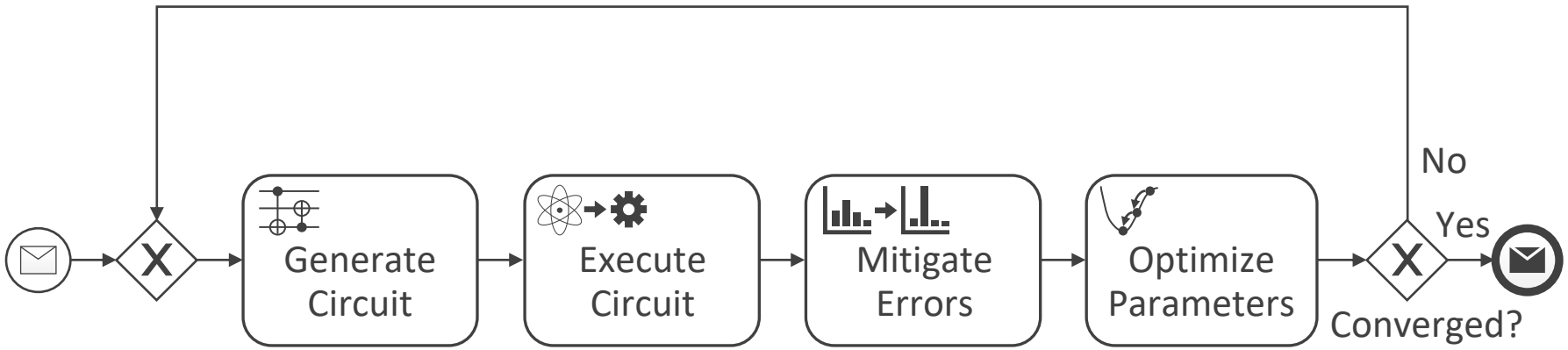
- Semantic:
  - Execution of a given quantum circuit
- Input and Output:
  - **Input:** Quantum circuit to execute
  - **Output:** Probability distribution resulting from the execution
- Configuration attributes :
  - **Provider:** Quantum Provider to use
  - **QPU:** Quantum device to use
  - **Shots*:** Number of circuit executions on the quantum device

* optional



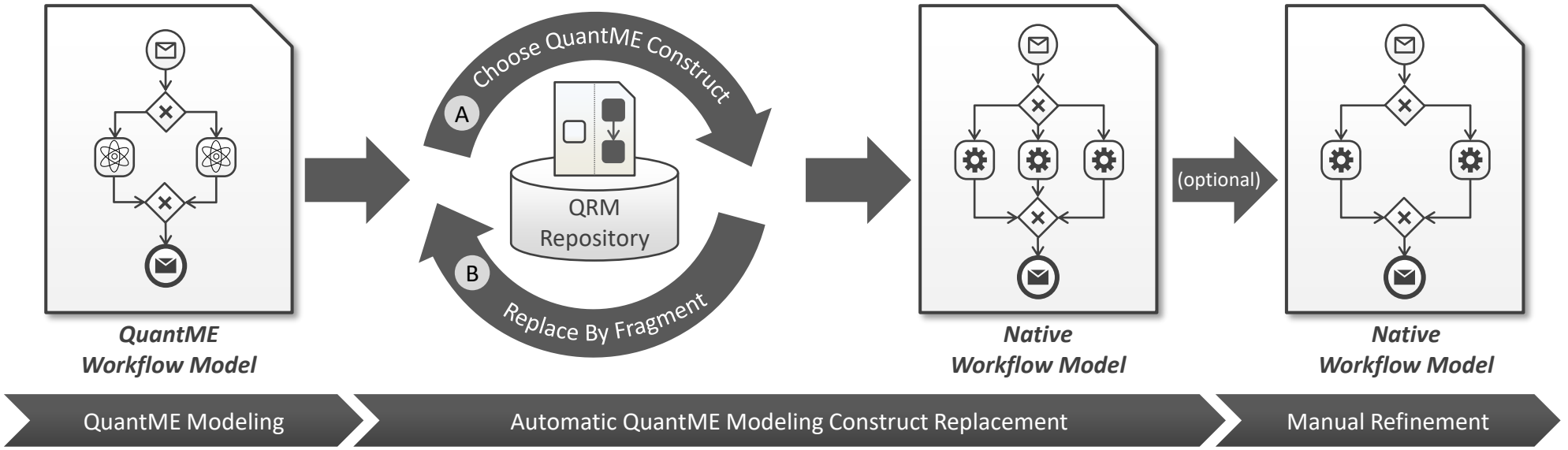


Exemplary Orchestration of a Variational Quantum Algorithm



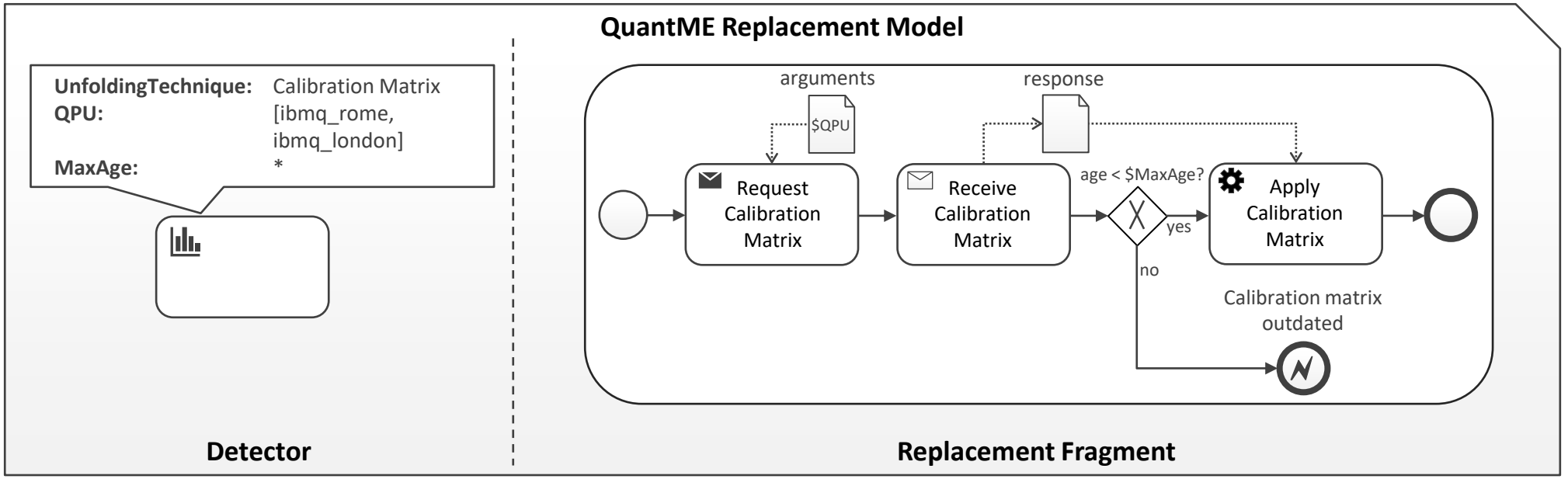
Transformation

- Transformation to native workflow language, e.g., BPMN
  - Portability
  - Compatibilty with existing workflow engines
- Transformation based on reusable workflow fragments



QuantME Replacment Models (QRMs)

- Defining QuantME tasks to replace together with replacing workflow fragments
- Exemplary QRM:



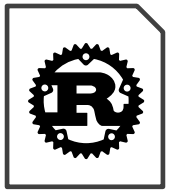
Views on Quantum Workflows

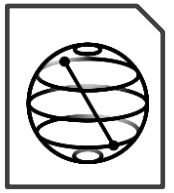
Hybrid Service Deployments

- To run workflows the required services must be available
- While some services are always available…




- Evolving domains, such as the quantum domain, often require custom-built services



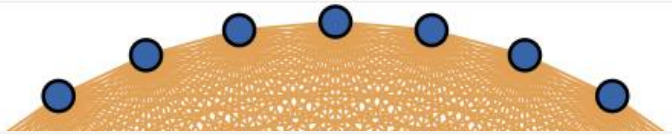
- These services must be deployed by the user

Introduction & Motivation

- Monitoring of hybrid quantum applications is complicated by:
  - Complexity of quantum and classical tasks
  - Heterogeneity of multi-cloud deployments

Introduction & Motivation

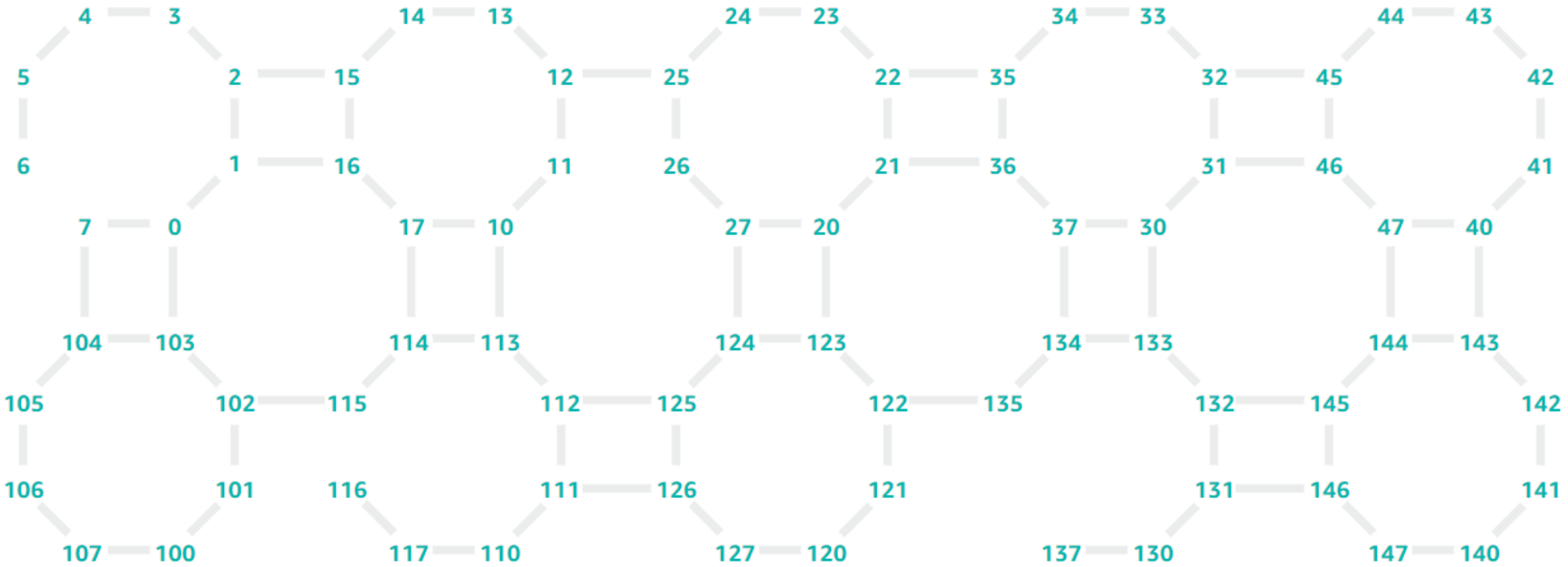
Topology



Device specs | Qubit specs | Edge specs | JSON

	Average	Median
	24.978	22.098

Topology

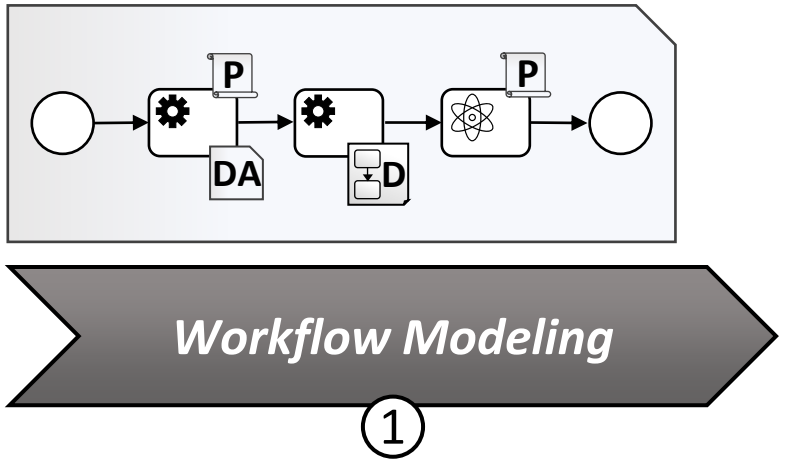


					0.002	99.619 ± 0.006	96.900	99.550
14	22.098	35.754	99.824 ± 0.004		99.753 ± 0.005	96.900	99.950

Process Views

- Process views visualize workflows at different abstraction levels
- They reduce complexity by:
  - Hiding unnecessary details
  - Filtering or enriching data
  - Aggregating information
  - …

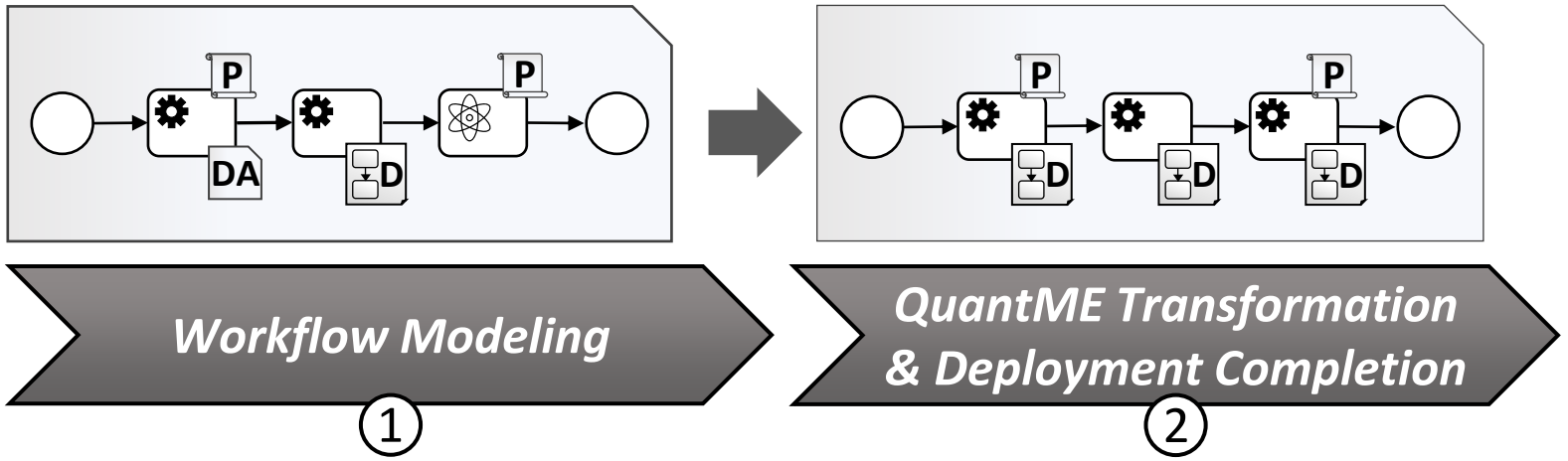
Observability for Quantum Workflows



Legend:

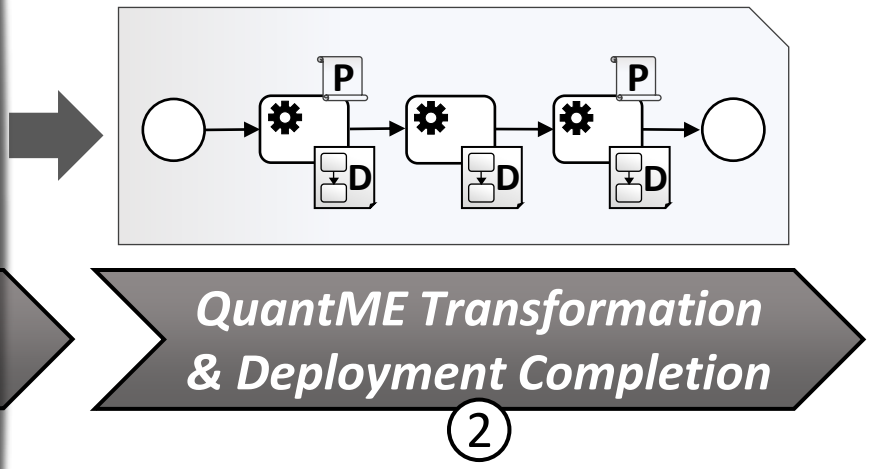
- P — Policy
- DA — Deployment Artifact
- D — Deployment Model
- Self-Contained Application Package

Observability for Quantum Workflows



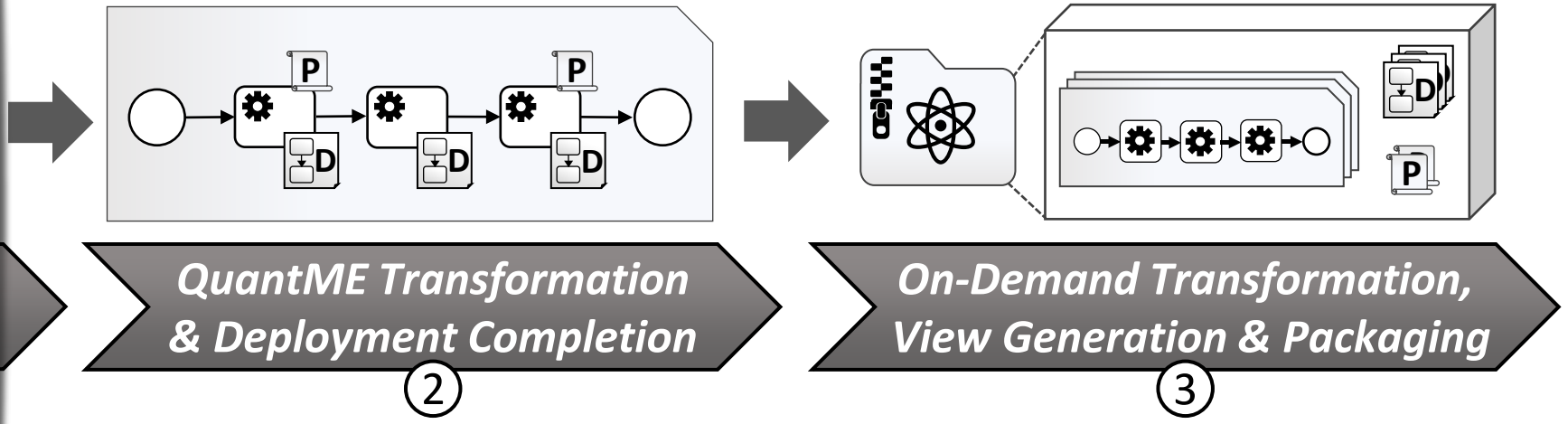
Legend: P Policy; DA Deployment Artifact; D Deployment Model; Self-Contained Application Package

Observability for Quantum Workflows



Legend: P Policy | DA Deployment Artifact | D Deployment Model | Self-Contained Application Package

Observability for Quantum Workflows



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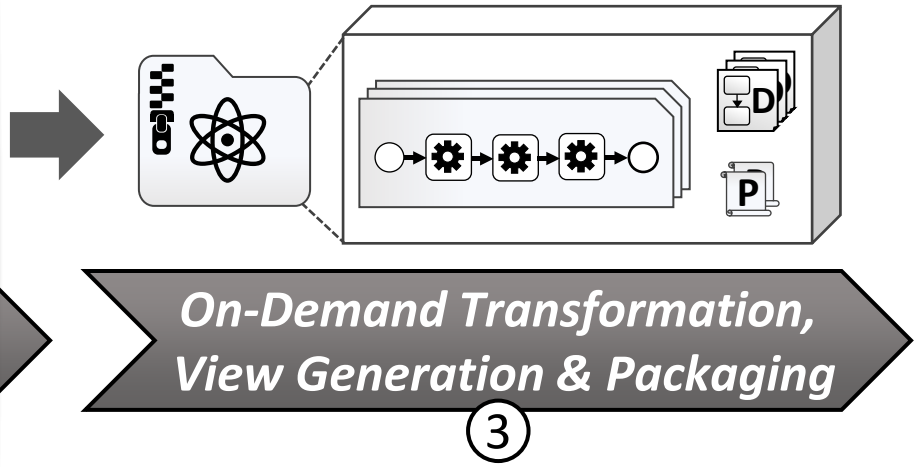
Observability for Quantum Workflows



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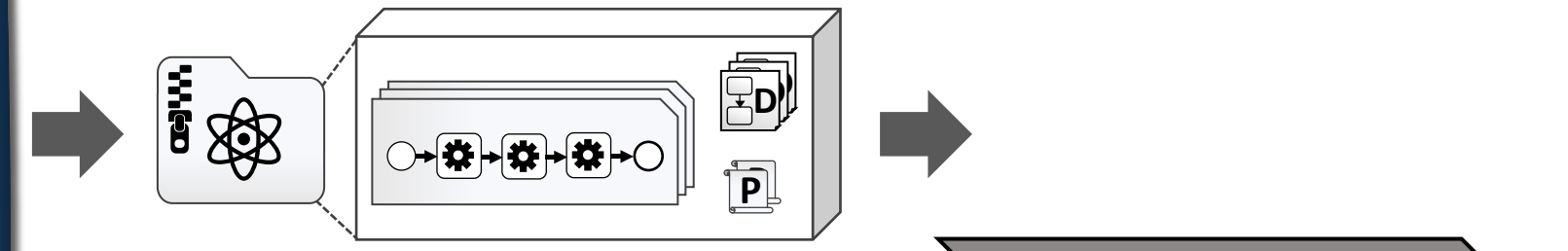
Observability for Quantum Workflows



On-Demand Transformation, View Generation & Packaging

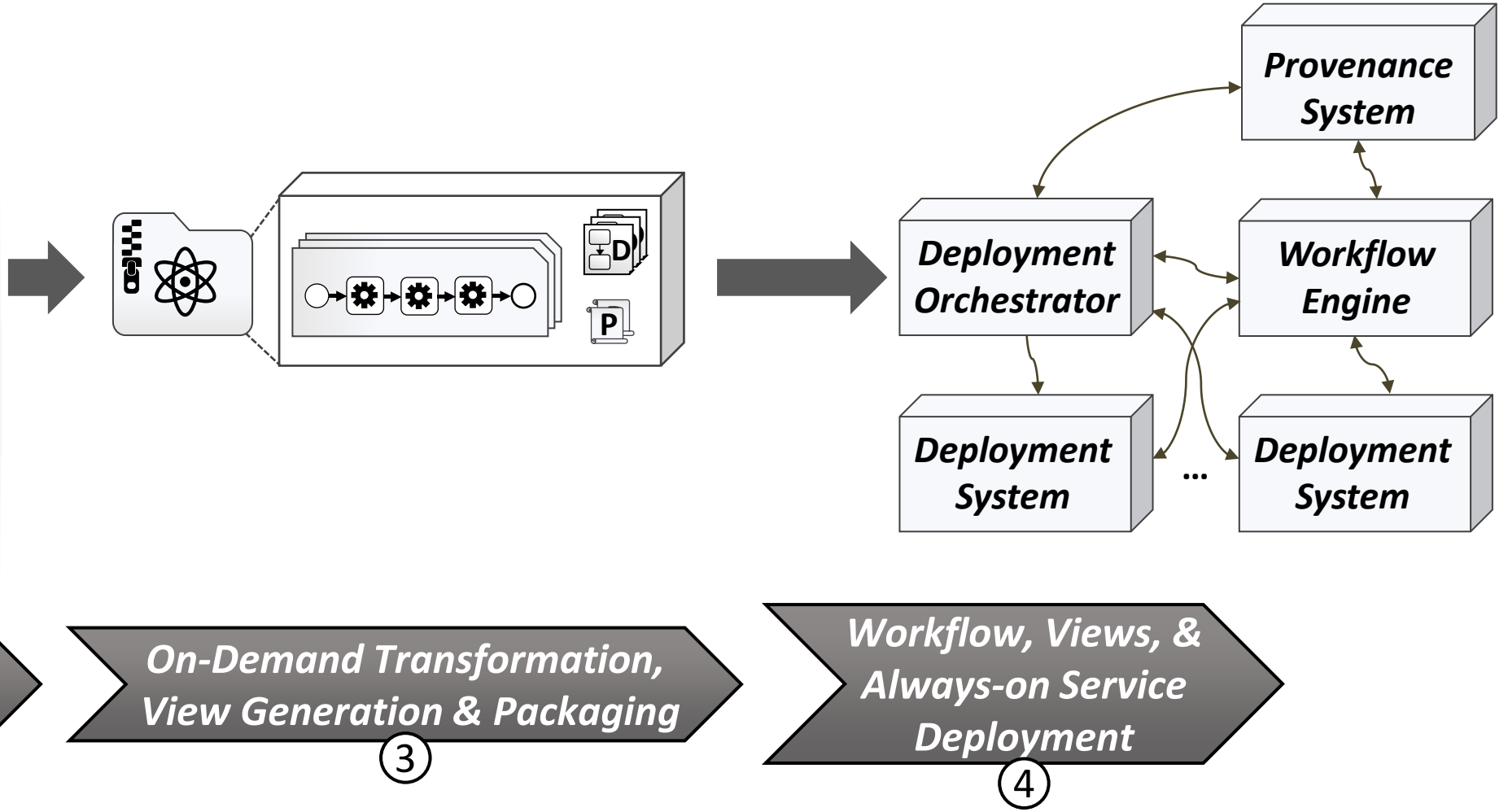
3

Workflow, Views, & Always-on Service Deployment

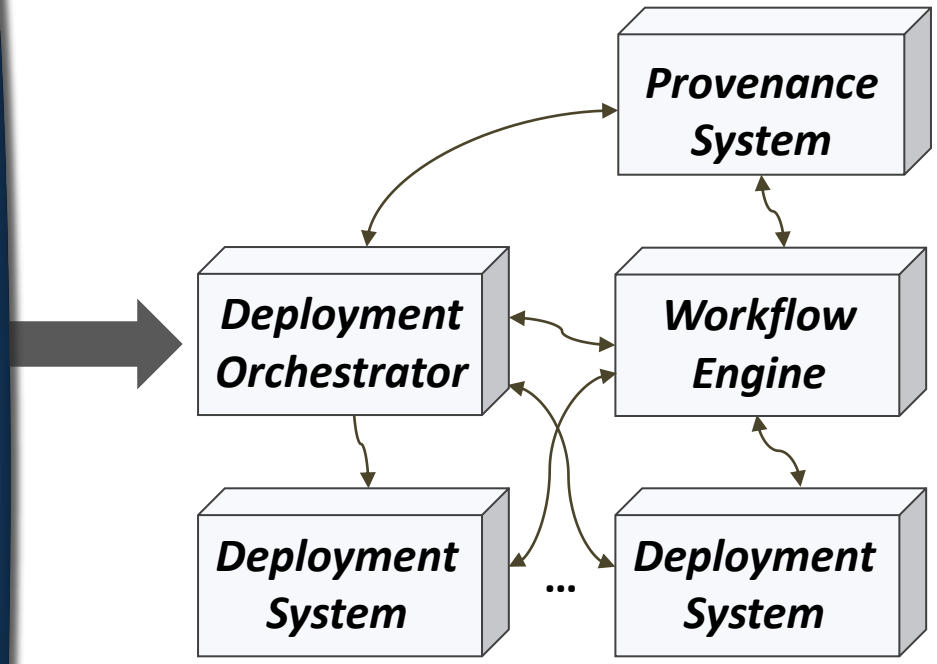
4

Legend: P Policy; DA Deployment Artifact; D Deployment Model; Self-Contained Application Package

Observability for Quantum Workflows



Observability for Quantum Workflows

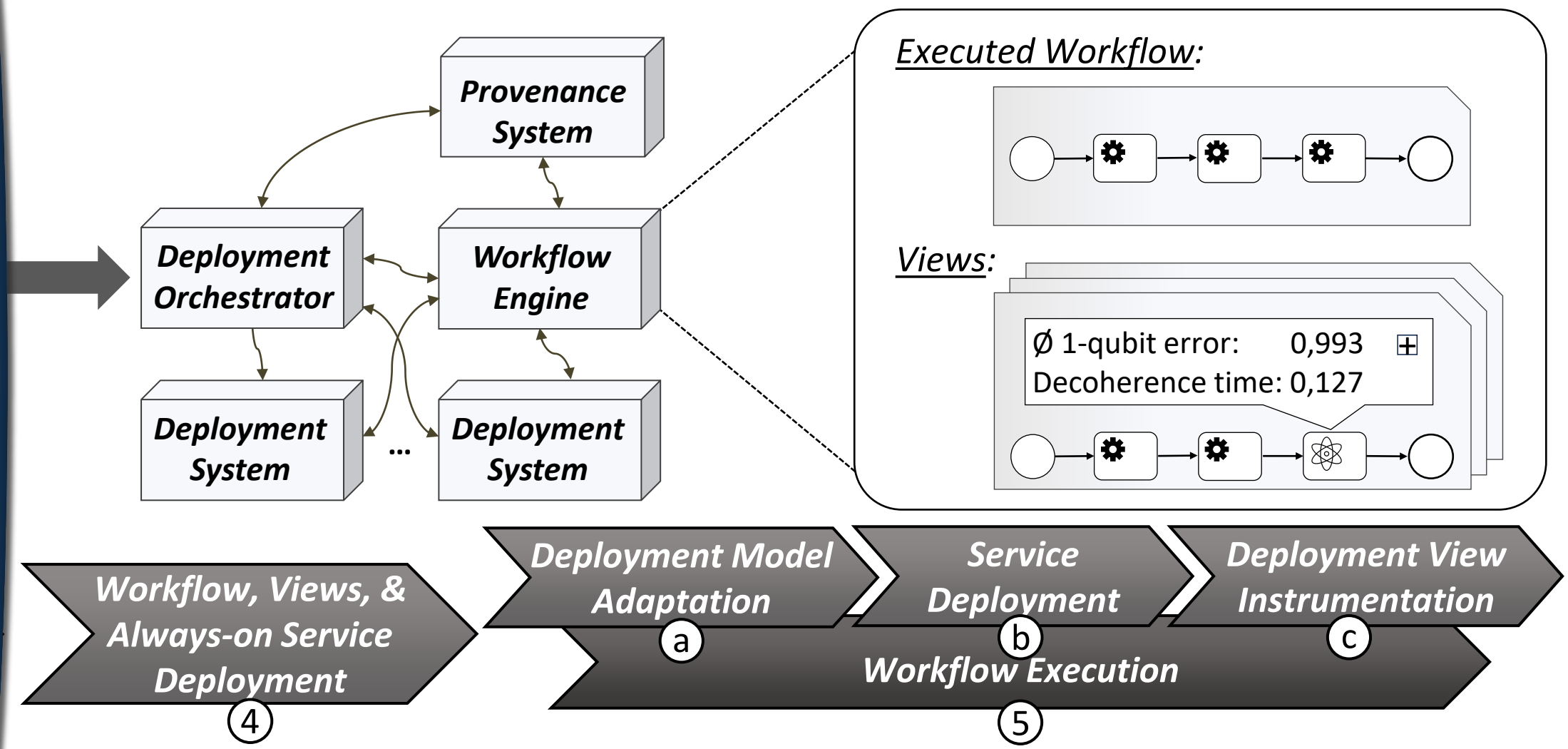


Workflow, Views, & Always-on Service Deployment

④

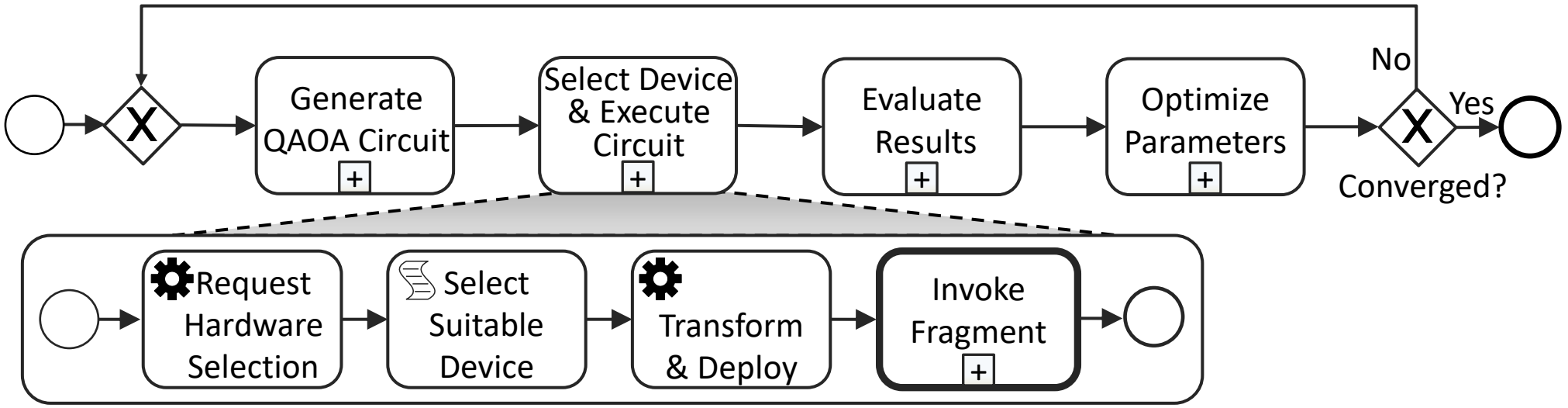
Legend: P Policy | DA Deployment Artifact | D Deployment Model | Self-Contained Application Package

Observability for Quantum Workflows



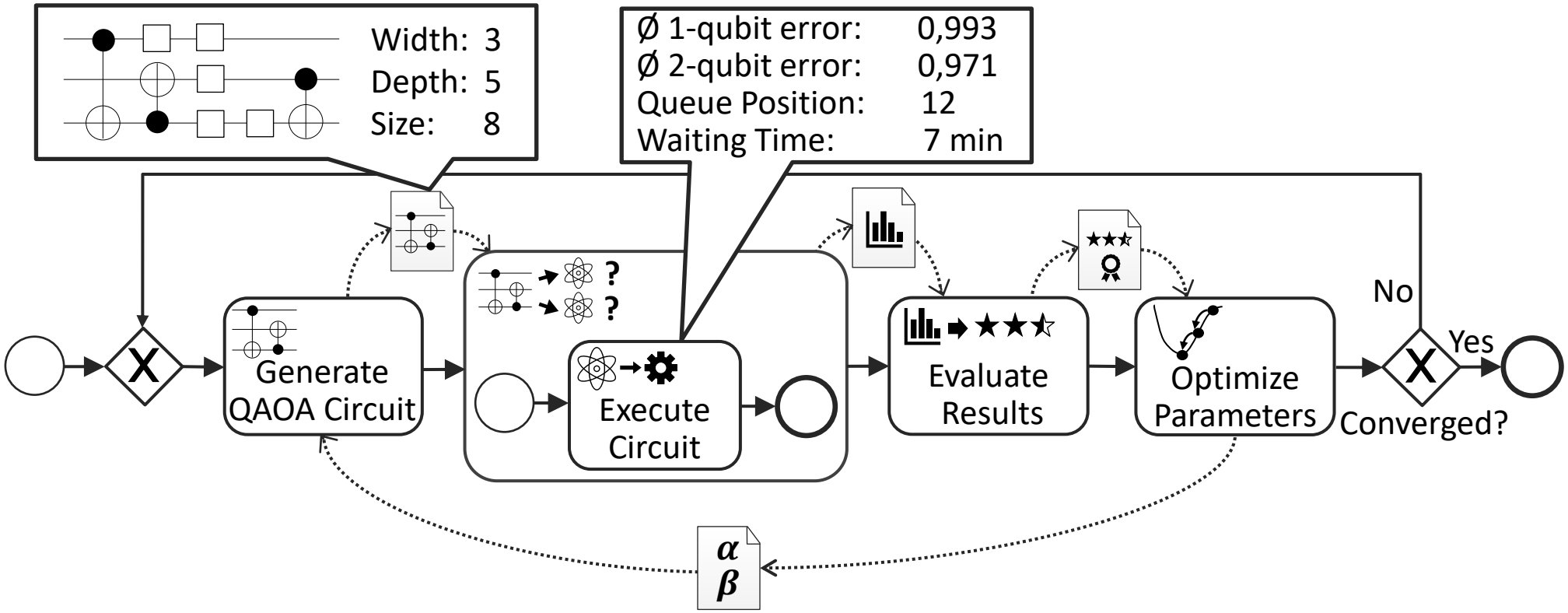
Process Views for Quantum Workflows

Workflow



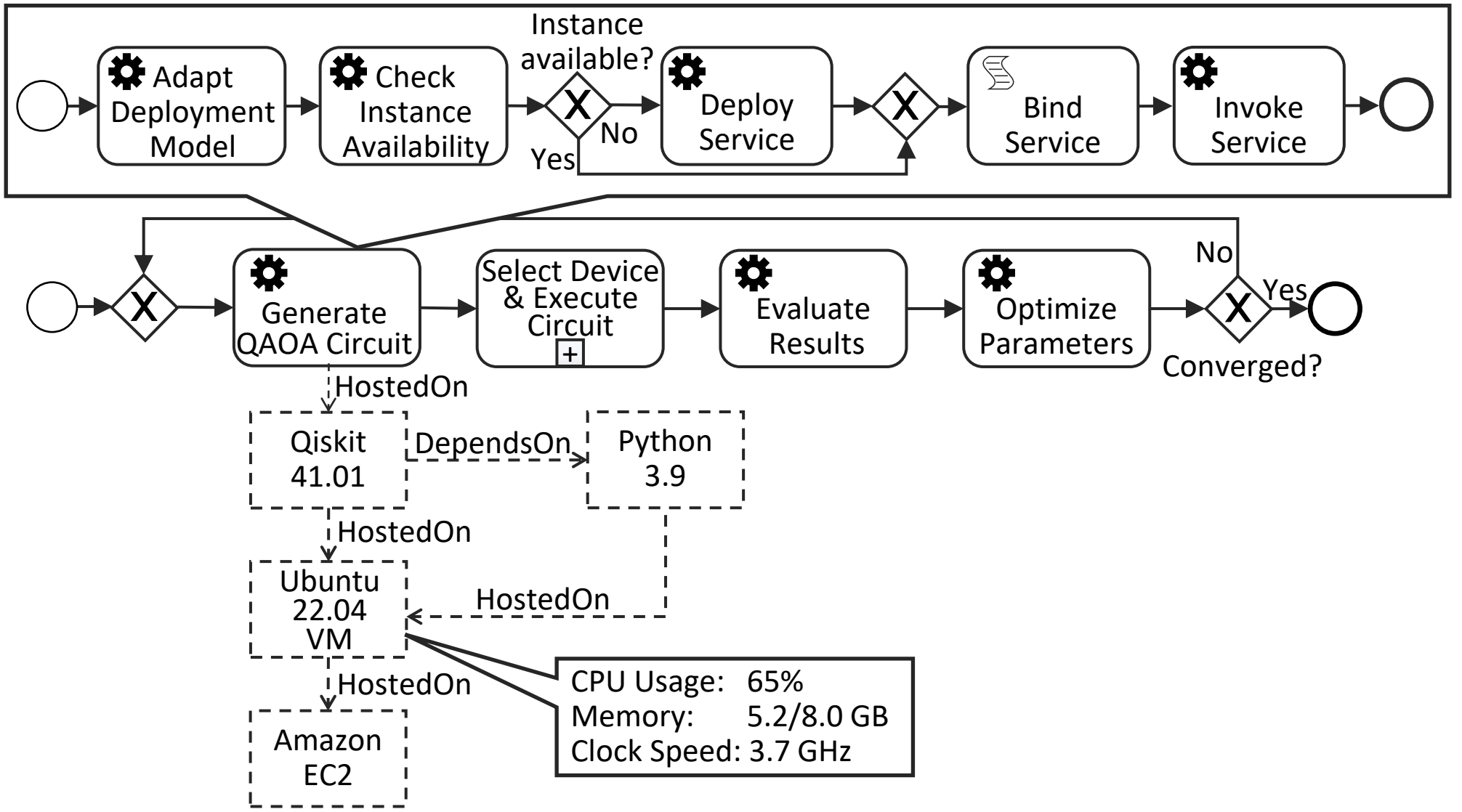
Process Views for Quantum Workflows

Quantum View



Process Views for Quantum Workflows

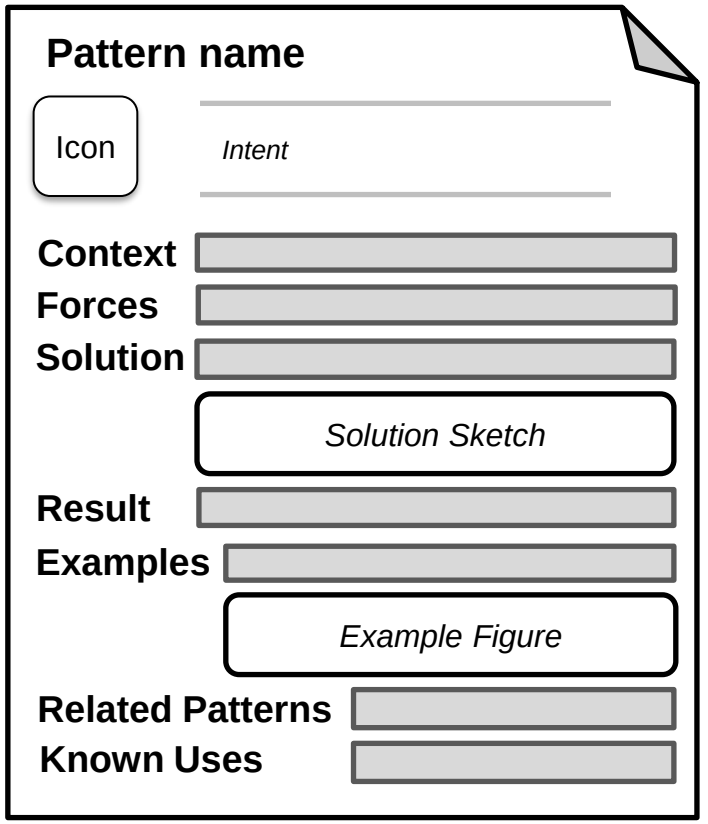
Deployment View



Pattern-based Modeling of Quantum Applications

Pattern Language for Quantum Algorithms [1]

- **Pattern:**
  - Structured document
  - Abstract description of a proven solution for a recurring problem
- **Pattern Language:**
  - Interconnected patterns of the same domain



Pattern Language for Quantum Algorithms [1]

Program Flow

- Quantum-Classic Split
- VQA
- Warm-Start
- QAOA
- ...

State Preparation

- Basis Encoding
- Angle Encoding
- ...

Unitary Transformations

- Phase Shift
- Amplitude Amplification
- ...

Execution

- Prioritized Execution
- Orchestrated Execution
- ...

Error Handling

- Error Correction
- Gate Error Mitigation
- ...

Cutting

- Circuit Cutting
- ...

Quantum States

- Uniform Super-position
- Creating Entangle-ment

Measurement

- Post-selective Measurement

[1] F. Leymann, "Towards a Pattern Language for Quantum Algorithms," *QTOP*, Springer, 2019.
[2] M. Weigold et al., "Expanding Data Encoding Patterns For Quantum Algorithms," *ICSA-C*, IEEE, 2021.
[3] M. Weigold et al., "Patterns for Hybrid Quantum Algorithms," *SummerSoC*, Springer, 2021.
[4] M. Beisel et al., "Patterns for Quantum Error Handling," *PATTERNS*, XPS, 2022.
[5] F. Bühler et al., "Patterns for Quantum Software Development," PATTERNS, XPS, 2023.
[6] M. Bechtold et al. "Patterns for Quantum Circuit Cutting," PLoP, Hillside, 2023.
[7] D. Georg et al. "Execution Patterns for Quantum Applications," ICSOFT, SciTePress, 2023.

Quantum Computing Patterns

Cards Graph

Filter
Type to filter

Patterns Candidates

Uniform Superposition

Details

Wire Cut

Details

Gate Cut

Details

Circuit Cutting

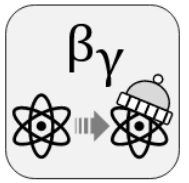
Details

Biased Initial State


Details

Pre-Trained Feature Extractor

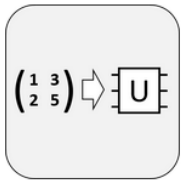
Details

Variational Parameter Transfer


Details

Chained Optimization

Details

Matrix Encoding


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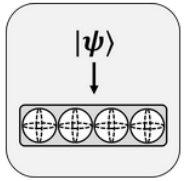
Initialization


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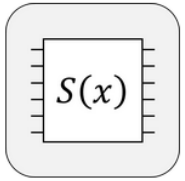
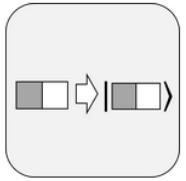
Schmidt Decomposition


Details

Uncompute

Details

Basis Encoding

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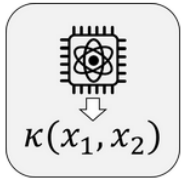
Quantum-Classic Split


Details

Quantum Kernel Estimator (QKE)


Details

Error Correction

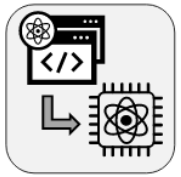
Details

Gate Error Mitigation

Details

Readout Error Mitigation

Details

Ad-hoc Hybrid Code Execution

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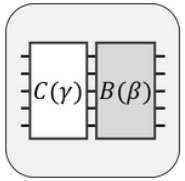
Alternating Operator Ansatz (AOA)


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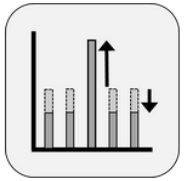
Amplitude Amplification

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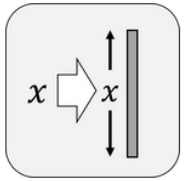
Amplitude Encoding


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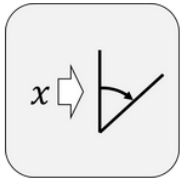
Angle Encoding


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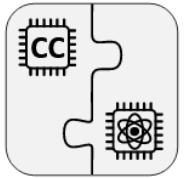
Classical-Quantum Interface


Details

Creating Entanglement

Details

Function Table

Details

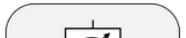
Hybrid Module


Details

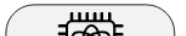
Oracle


Orchestrated Execution


Phase Shift


Post-Selective Measurement


Pre-deployed Execution

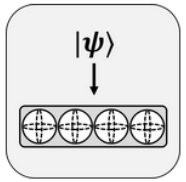

Prioritized Execution


Quantum Approximate Optimization Algorithm (QAOA)


Quantum Associative Memory (QuAM)


Quantum Circuit Translator


Initialization



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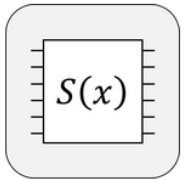
Schmidt Decomposition

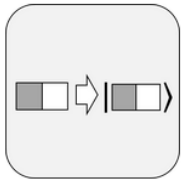


Details

Uncompute

Details

Basis Encoding



Details

Quantum-Classic Split

Details

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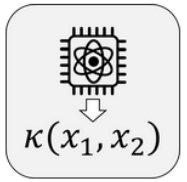


Details

Error Correction

Details

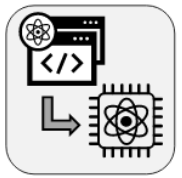
Gate Error Mitigation

Details

Readout Error Mitigation

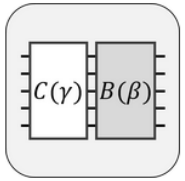
Details

Ad-hoc Hybrid Code Execution



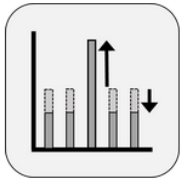
Details

Alternating Operator Ansatz (AOA)



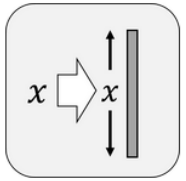
Details

Amplitude Amplification



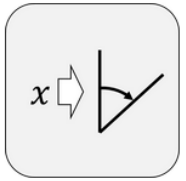
Details

Amplitude Encoding



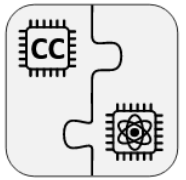
Details

Angle Encoding



Details

Classical-Quantum Interface

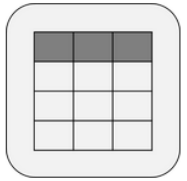


Details

Creating Entanglement

Details

Function Table



Details

Hybrid Module

Details

Oracle

Details

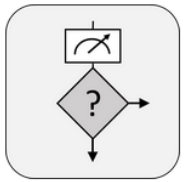
Orchestrated Execution

Details

Phase Shift

Details

Post-Selective Measurement

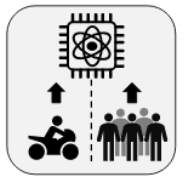


Details

Pre-deployed Execution

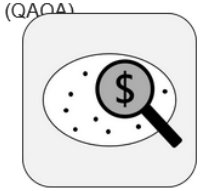
Details

Prioritized Execution



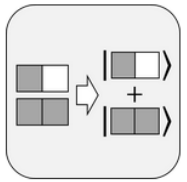
Details

Quantum Approximate Optimization Algorithm (QAOA)



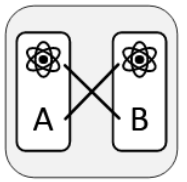
Details

Quantum Associative Memory (QuAM)



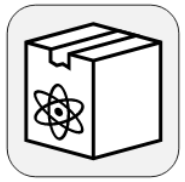
Details

Quantum Circuit Translator



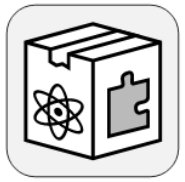
Details

Quantum Module



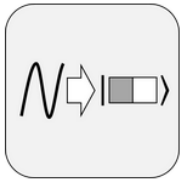
Details

Quantum Module Template



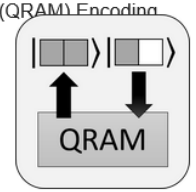
Details

Quantum Phase Estimation



Details

Quantum Random Access Memory (QRAM) Encoding

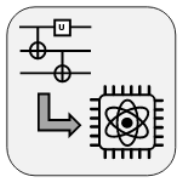


Details

Speedup via Verifying

Details

Standalone Circuit Execution



Details

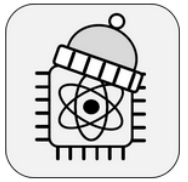
Variational Quantum Algorithm (VQA)

Details

Variational Quantum Eigensolver (VQE)

Details

Warm Start



Details

Concrete Solutions

- Facilitate the application of patterns by providing implementations of a pattern
- For example:
  - Code Snippets
  - Quantum Circuits
  - …