Some Recent Musings on Quantum Computing

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Based on joint work with M. Schönberger, M. Franz, L. Wolf, I. Sax, T. Krüger (OTH)
and M. Periyasamy, A. Plinge, D. D. Scherer, S. Scherzinger, Ch. Ufrecht, Ch. Mutschler

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Quantum Computing Algorithms & Applications

QC: Research Necessities

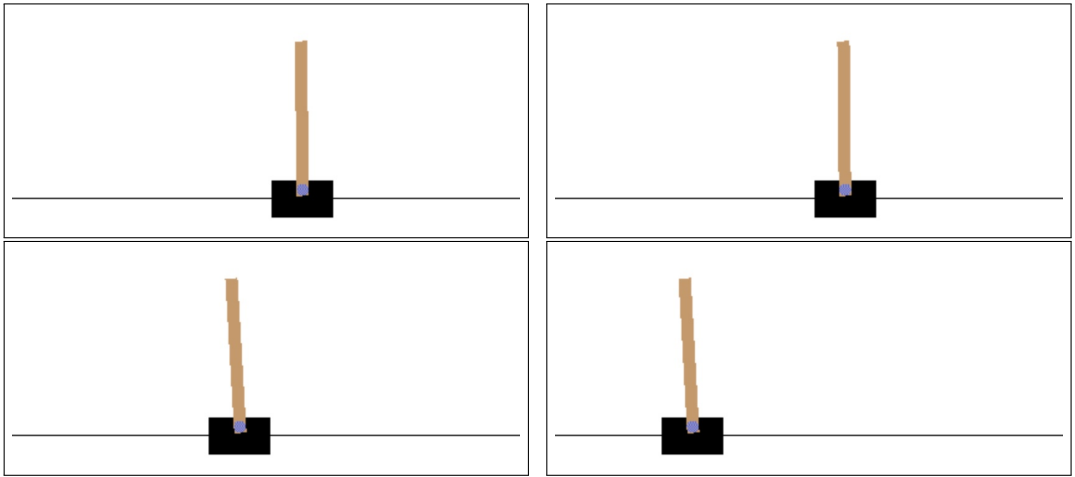
1. Explore precise limits (fundamental & technical)
2. **Consider problems holistically**
3. **Maximise utility**

Possible Applications

- Reinforcement Learning
- Optimisation
- Databases

Reinforcement Learning

Reinforcement Learning I



Ingredients

- State
- Action
- Reward/Punishment
- Tradeoff between current and future gains

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Bellman Optimality Equation

$$Q_*(s,a) = \mathbb{E}\Big[R_t + \gamma \max_{a'} Q_*(S_{t+1}, a') \mid S_t = s, A_t = a\Big]$$

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Advantage & Disadvantage

- Switch between *exploration* and *exploitation*
- Q function is hard to compute

Bellman Optimality Equation

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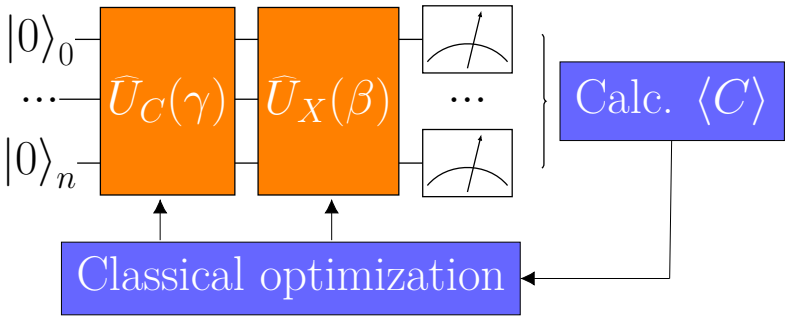
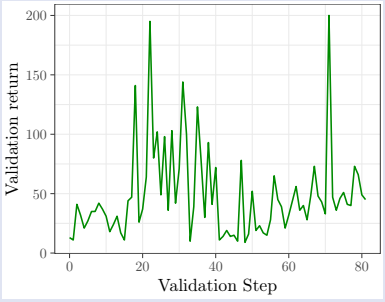
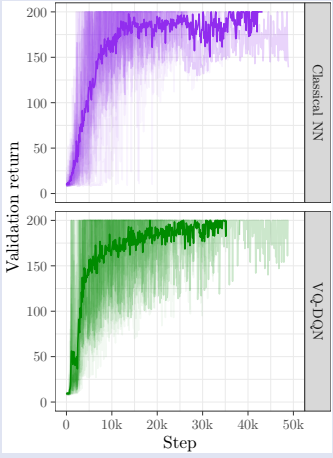

$|0\rangle_0$
$\cdots$
$|0\rangle_n$
$\widehat{U}_C(\gamma)$
$\widehat{U}_X(\beta)$
$\cdots$
Calc. $\langle C \rangle$
Classical optimization

IBMQ performance



QRL: Classical vs. hybrid VQ-DQN



Optimisation


D:WAVE 2000Q
D:WAVE
D:WAVE 2000Q
D:WAVE

Boolean Satisfiability

$$f(\vec{x}) = (x_1 \vee \bar{x}_2 \vee \bar{x}_4) \wedge (x_2 \vee x_3 \vee x_5) \wedge (x_1 \vee x_4 \vee \bar{x}_6)$$

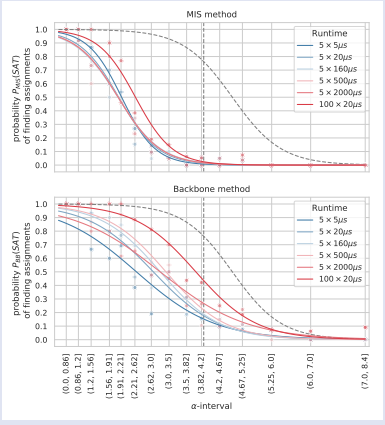
Annealers and QUBOs

$$\min_{\vec{x}} \left(\sum_i c_{ii} x_i + \sum_{i \neq j} c_{ij} x_i x_j \right)$$

Reductions

- Choi: k-SAT $\leq_{\mathrm{p}}$ MIS $\leq_{\mathrm{p}}$ QUBO
- Backbone

$\alpha = |C|/|V|$



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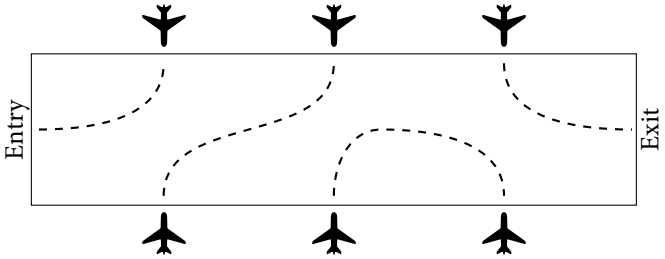
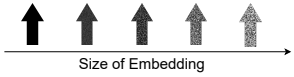
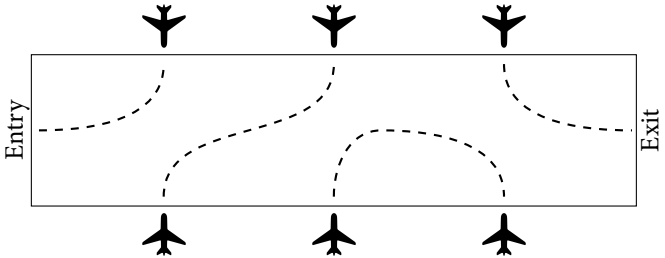
Maximise Utility

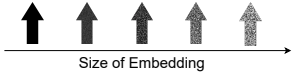




$$\min_{\vec{x}} \left(\sum_{i \in I} c_{ii} x_i + \sum_{(i,j) \in K} c_{ij} x_i x_j \right)$$

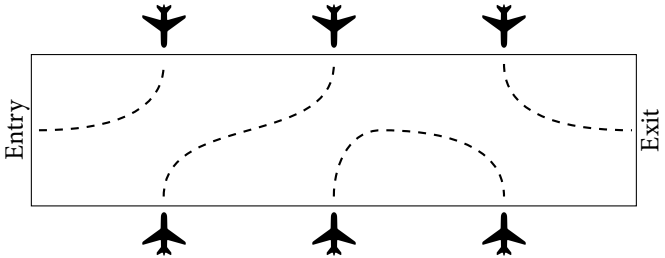
Maximise Utility

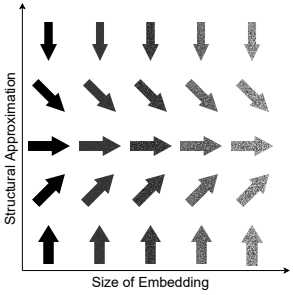




$$\min_{\vec{x}} \Bigg(\underbrace{\sum_{i \in I} c_{ii} x_i + \sum_{(i,j) \in K} c_{ij} x_i x_j}_{\text{Correctness}} + \underbrace{\sum_{i \in I'} c_{ii} x_i + \sum_{(i,j) \in K'} c_{ij} x_i x_j}_{\text{Optimisation}} \Bigg)$$

Maximise Utility





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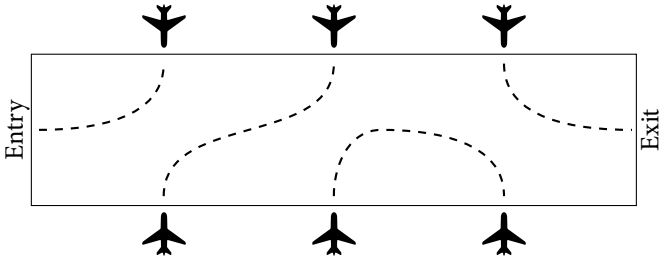
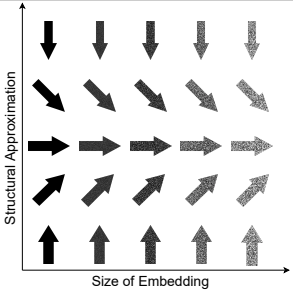
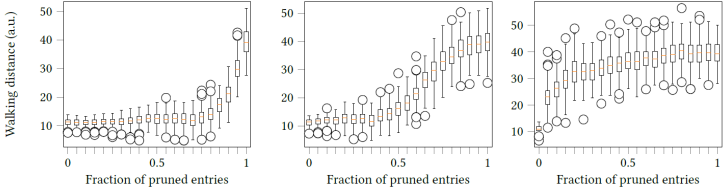
Maximise Utility

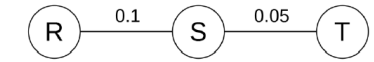
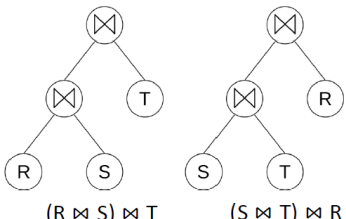






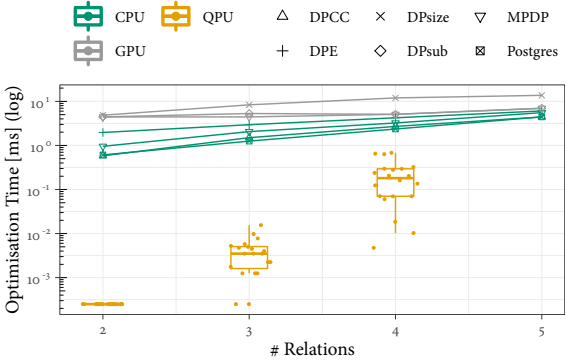
Databases

Join Ordering Overview

Input			The query graph with the relations **R**, **S** and **T** and two predicates.
Solutions			**Two possible left-deep join trees** representing different join permutations.
Resulting cost	51,000	100,000	Vastly different costs.

D-Wave Quantum Annealing

- Comparison to classical DP
- Speedups for small queries[3]
- But: Limits quickly reached



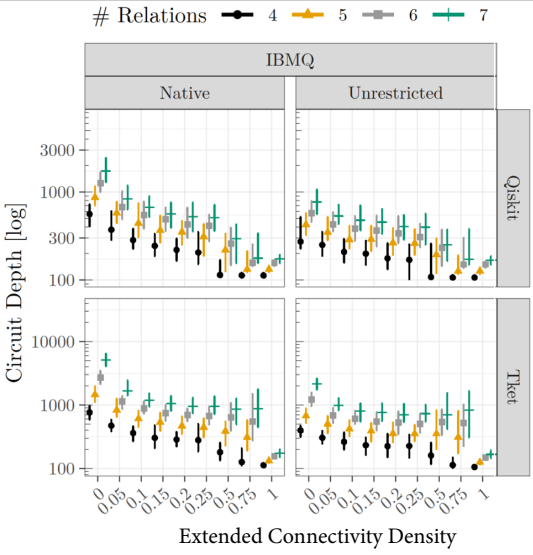
[3]Note that we consider simplified queries for the QPU, to avoid discretisation issues.

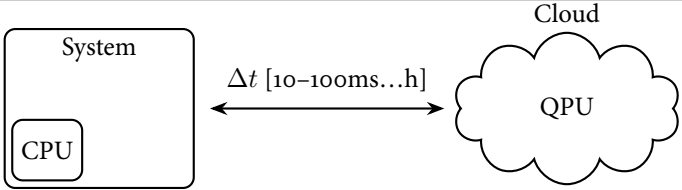
Extrapolating QPUs

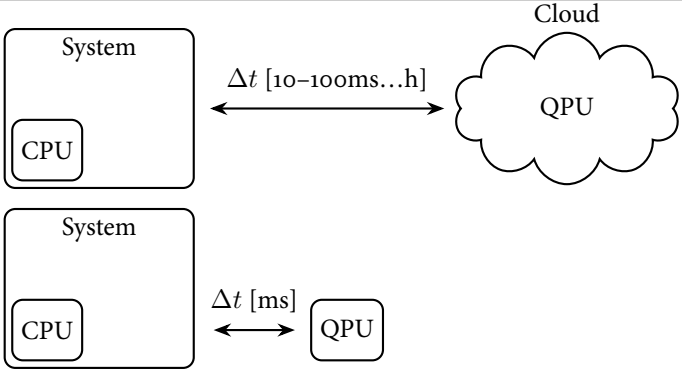
- Criteria:
  - Problem size
  - Connectivity
  - Gate sets
- Topologies:
  - IBM Q
  - Rigetti
  - IonQ

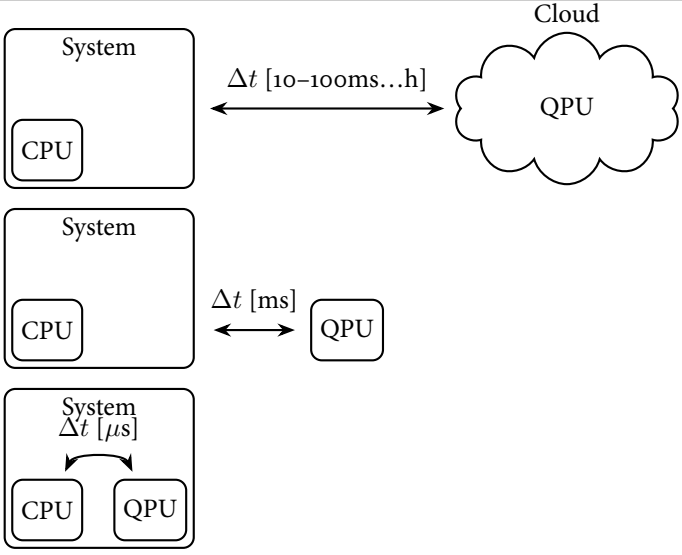
Impact on IBM Q

- Higher connectivity: Drastic impact
- Gate sets: Moderate impact

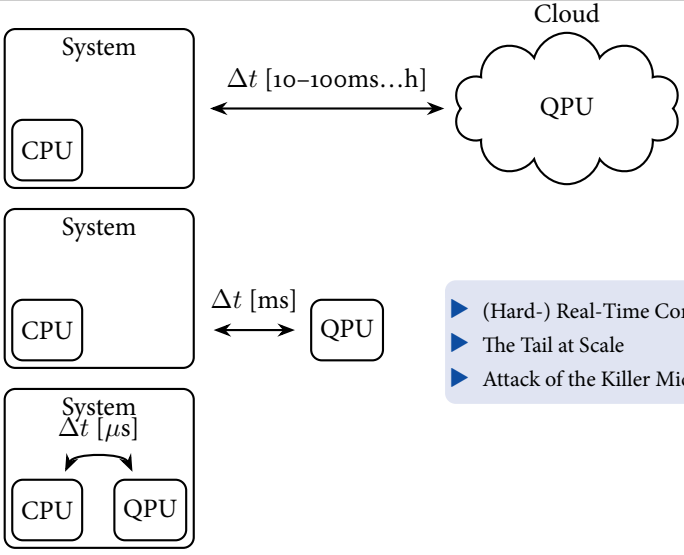



System
CPU
Δt [10–100ms…h]
Cloud
QPU

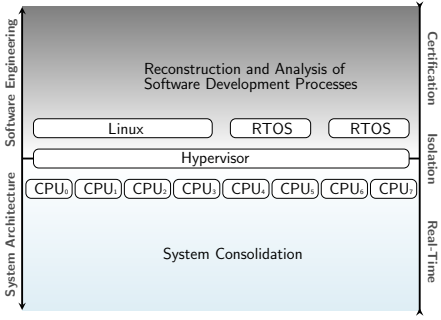

Cloud
System
CPU
Δt [10–100ms…h]
QPU
System
CPU
Δt [ms]
QPU


Cloud
System
CPU
Δt [10–100ms…h]
QPU
System
CPU
Δt [ms]
QPU
System
Δt [μs]
CPU
QPU

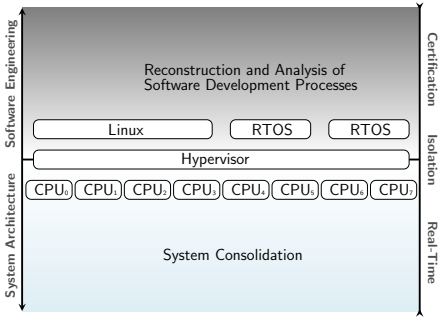
Latency and Jitter and Integration

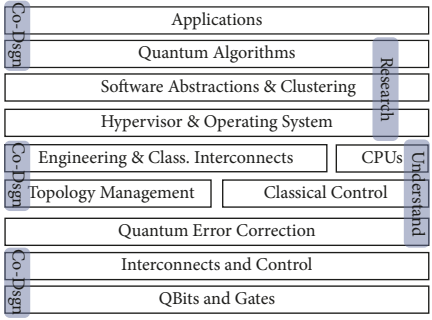


- (Hard-) Real-Time Computing
- The Tail at Scale
- Attack of the Killer Microseconds



OTH Regensburg: > 300 Commits to Jailhouse@GitHub
R. Ramsauer, D. Lohmann, WM: *Look mum, no VM exits! (almost)*, Proc. 13th Workshop on Operating Systems Platforms for Embedded Real-Time Applications (OSPERT) (2017)





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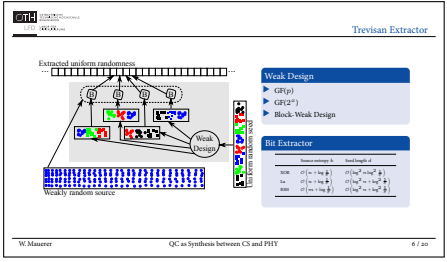
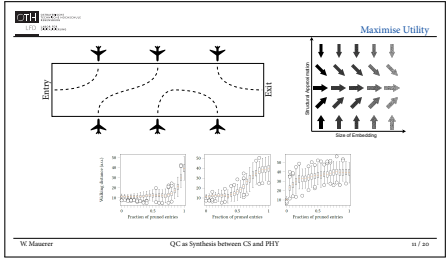
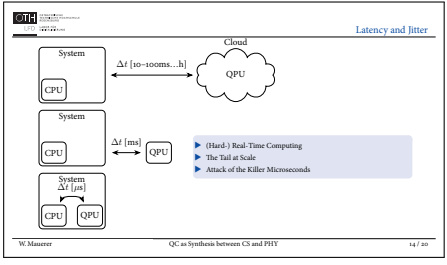
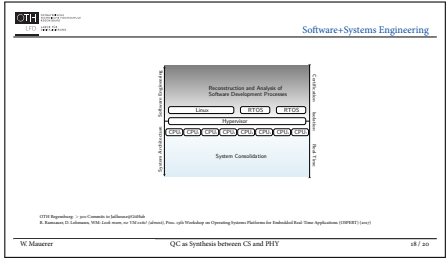
Thank you!


Trevisan Extractor
Extracted uniform randomness
Weak Design
Weakly random source
Uniform random word
Weak Design
GF(p)
GF(2^n)
Block-Weak Design
Bit Extractor
W. Maurerer
QC as Synthesis between CS and PHY
8 / 20


Maximise Utility
Entry
Exit
Structural Separation
Size of Embedding
Fraction of pruned entries
W. Maurerer
QC as Synthesis between CS and PHY
11 / 20


Latency and Jitter
Cloud
System
CPU
QPU
Δt [10–100ms…h]
Δt [ms]
(Hard-) Real-Time Computing
The Tail at Scale
Attack of the Killer Microseconds
System Δt [μs]
W. Maurerer
QC as Synthesis between CS and PHY
14 / 20


Software+Systems Engineering
Reconstruction and Analysis of Software Development Processes
Linux
RTOS
RTOS
Hypervisor
CPU0
CPU1
CPU2
CPU3
CPU4
CPU5
CPU6
CPU7
System Consolidation
Software Engineering
System Architecture
Config-ware
Isolation
Real-Time
W. Maurerer
QC as Synthesis between CS and PHY
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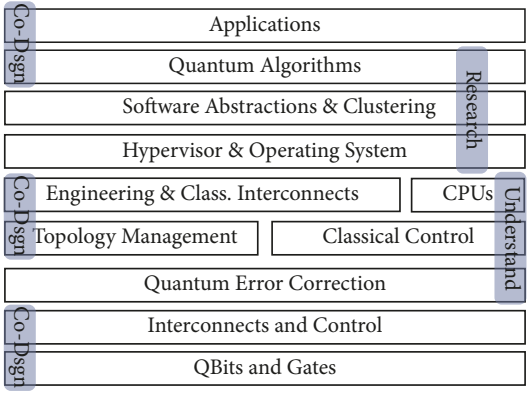
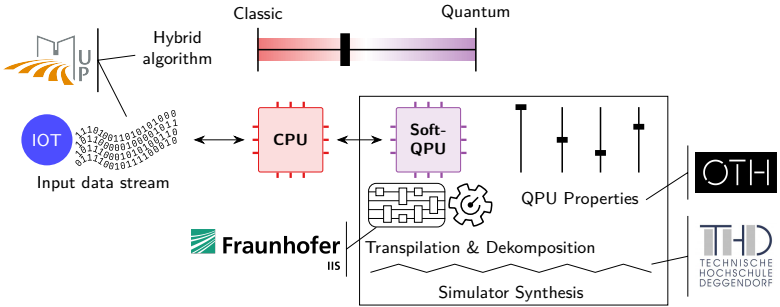
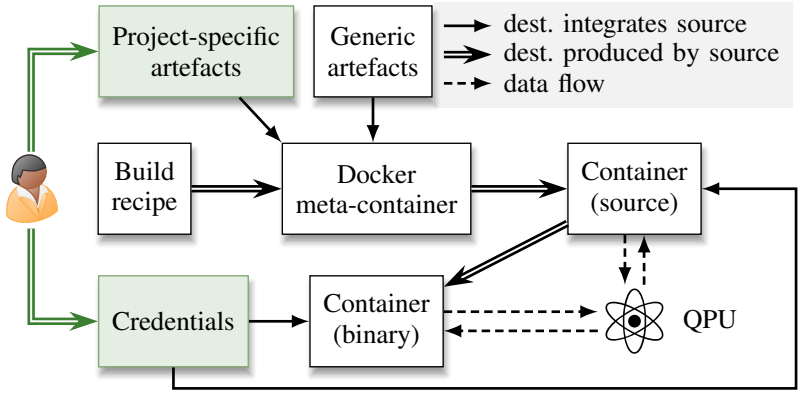
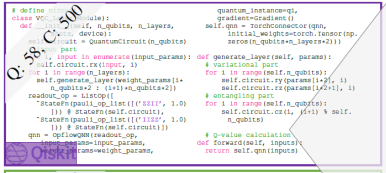
Appendix/Backup


Co-Dsgn
Applications
Co-Dsgn
Quantum Algorithms
Research
Software Abstractions & Clustering
Hypervisor & Operating System
Co-Dsgn
Engineering & Class. Interconnects
CPUs
Understand
Co-Dsgn
Topology Management
Classical Control
Understand
Quantum Error Correction
Co-Dsgn
Interconnects and Control
Co-Dsgn
QBits and Gates


Classic
Quantum
Hybrid algorithm
IOT
Input data stream
CPU
Soft-QPU
QPU Properties
Fraunhofer IIS
Transpilation & Dekomposition
Simulator Synthesis
OTH
THD TECHNISCHE HOCHSCHULE DEGGENDORF

Quantum Reproducibility





Quantum Deep Q-Learning

Init replay buf $\mathbb{D}$, (target) VQC $\theta^{(-)}$
for $s \leftarrow 0$, steps do
  Sample $\mathbb{B} =$
    $(s_t, a_t, s_{t+1}, r_{t+1})\backslash\mathbb{D}$
  for all $b_i \in \mathbb{B}$ **do**
    ▷ Target
    $y_i \leftarrow \gamma \max_{a'} Q(s_{i+1}, a'; \theta^{-})$
    $q_i \leftarrow Q(s_i, a_i; \theta)$ ▷ Q-Value
  end for
  $L(\theta) \leftarrow (y - q)^2$ ▷ Loss
  Update θ param shift rule [36], [47])
  if $s \bmod \text{update} = 0$ **then**
    $\theta^{-} \leftarrow \theta$
  end if
end for

Multi Query Optimization

Init MQO QUBO qm, circ. params β, γ
$c_{\text{lin}}, c_{\text{qdr}} \leftarrow \text{IsingCoeffs}(qm)$
$hl \leftarrow \{\}$
for $k \leftarrow 0, p$ **do**
  $hl \leftarrow hl \frown \text{CostHam}(c_{\text{lin}}, c_{\text{qdr}})$
  $hl \leftarrow hl \frown \text{MixerHam}()$
end for
$qc \leftarrow \text{buildQCircuit}(hl, \beta, \gamma)$
Initialize classical optimizer opt
while ¬converged **do**
  $\beta, \gamma \leftarrow opt.\text{step}(qc, \beta, \gamma)$
end while
$r \leftarrow \text{sample}(qc, \beta, \gamma)$