QAR-Lab Site Report

and the

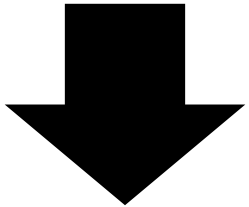
PlanQK Initiative

Workshop on Machine Learning for Quantum Technology

Thomas Gabor (thomas.gabor@ifi.lmu.de)

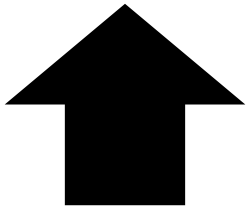
with thanks to Christoph Roch and Sebastian Feld

Machine Learning Solutions



Quantum Problems

Artificial Intelligence Problems



Quantum Solutions

QAR-Lab

QAR-Lab Site Report

QAR-Lab

Quantum Applications and Research Laboratory

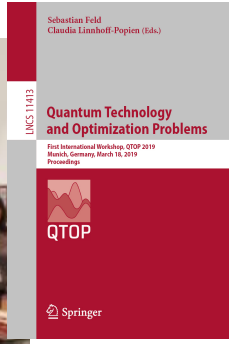
- young group at the chair for Mobile and Distributed Systems at the LMU Munich
- focused on **software** for quantum computers or similar machines
- interested in **near-term** applicability
- strong connections to **industry**

VOLKSWAGEN AKTIENGESELLSCHAFT

DATA:LAB MUNICH

AIRBUS

- In March, we hosted the First International Workshop on Quantum Technologies and Optimization Problems (**QTOP'19**) with 18 accepted papers and Springer LNCS proceedings.



3SAT

- Given a Boolean formula in CNF (with 3 literals per clause)
- Is this formula satisfiable?

- $(x_1 \vee x_2 \vee \overline{x_3}) \wedge (\overline{x_1} \vee \overline{x_4} \vee \overline{x_5})$
- Yes, for example choose $x_1 = T, x_2 = T, x_3 = T, x_4 = F, x_5 = T$

Thomas Gabor, Sebastian Zielinski, Sebastian Feld, Christoph Roch, Christian Seidel, Florian Neukart, Isabella Galter, Wolfgang Mauerer, and Claudia Linnhoff-Popien. Assessing Solution Quality of 3SAT on a Quantum Annealing Platform. In International Workshop on Quantum Technology and Optimization Problems. Springer, 2019.

3SAT

the canonical NP-hard problem

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The **hardness of a 3SAT problem** with *m* clauses over *n* variables depends on the ratio of clauses over variables $\alpha = \mathrm{m}/\mathrm{n}$

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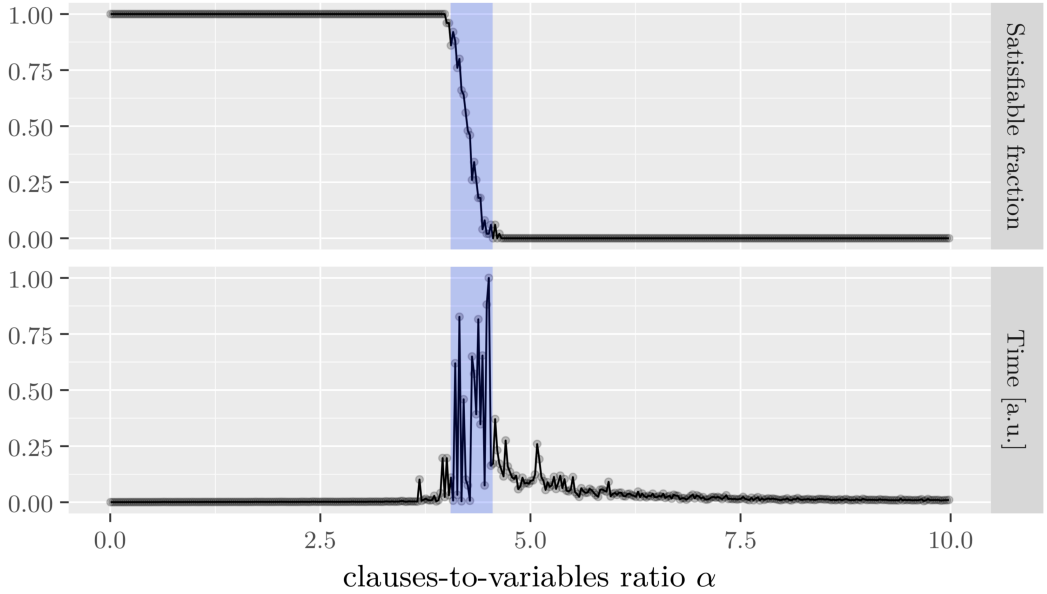
…on a classical machine…



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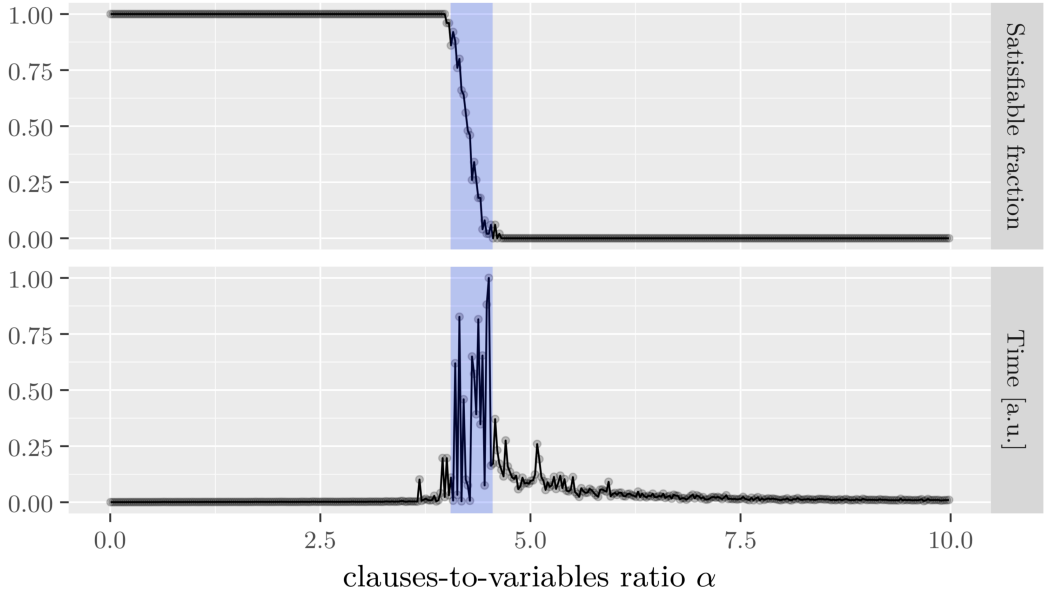


How does the Quantum Annealer behave?

3SAT instance

$F = (a \vee b \vee c) \wedge (a \vee \neg b \vee \neg c)$

Quantum Annealer
(D-Wave 2000Q)

3SAT instance

$F = (a \vee b \vee c) \wedge (a \vee \neg b \vee \neg c)$

QUBO instance

search

$$x \in \{0,1\}^n$$

so that

$$\sum_i \sum_{j<i} Q_{ij} x_i x_j + \sum_i Q_i x_i$$

is minimal

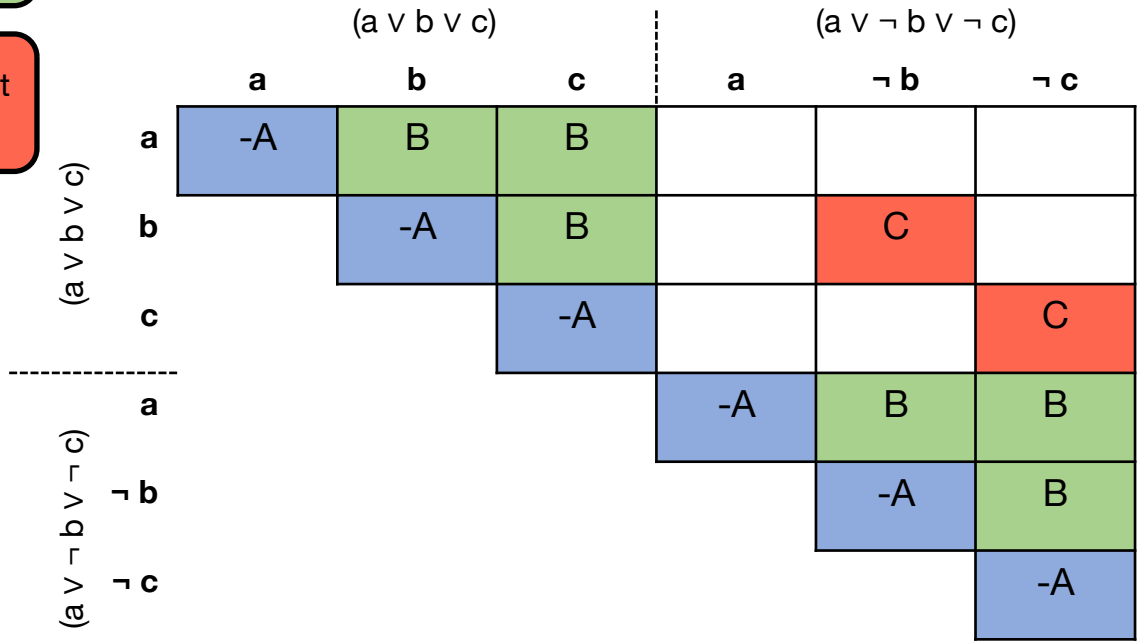
incentive to choose literals for proof

only one literal per clause needed for proof

chosen literals must not contradict each other

3SAT instance
$F = (a \vee b \vee c) \wedge (a \vee \neg b \vee \neg c)$

QUBO matrix



100,000 3SAT instances with 42 clauses

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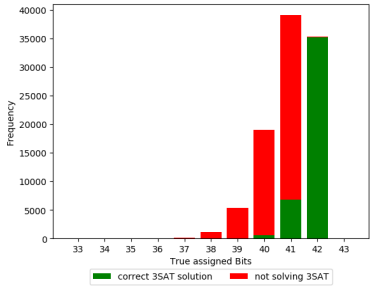
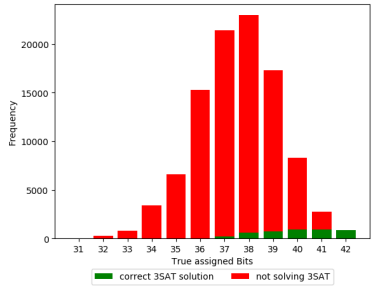
easy 3SAT instance



hard 3SAT instance

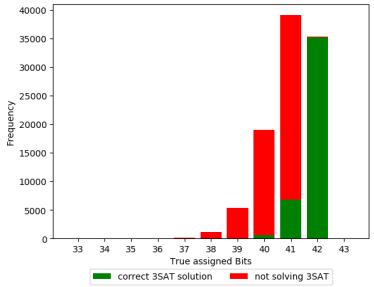


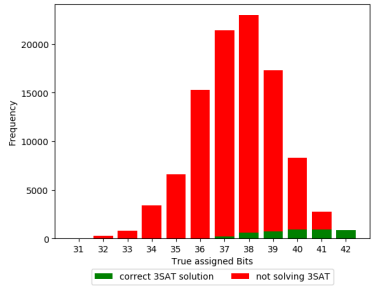
100,000 3SAT instances with 42 clauses

easy 3SAT instance

hard 3SAT instance

without D-Wave postprocessing





with D-Wave postprocessing (“optimizing”)

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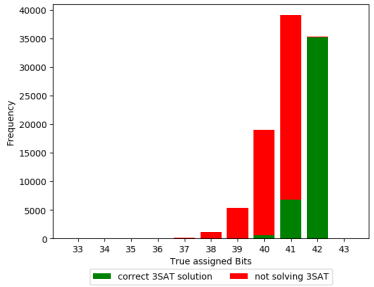

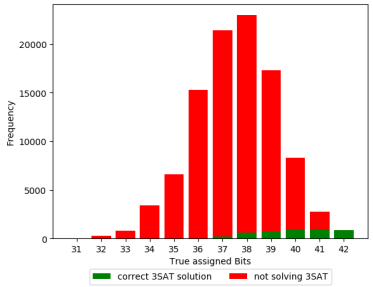

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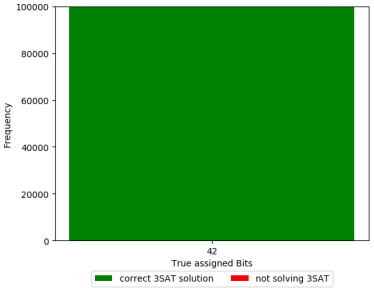

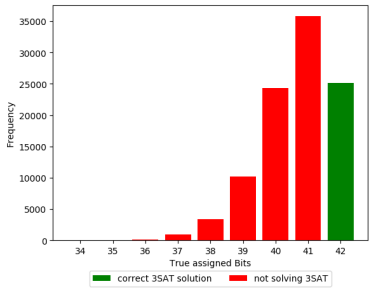

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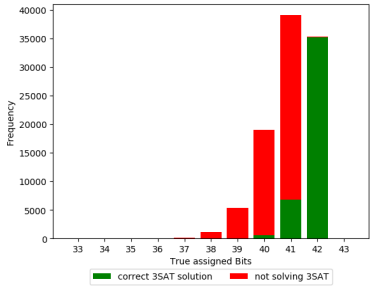

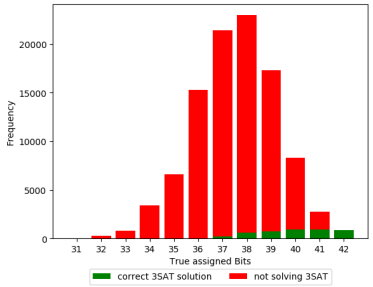

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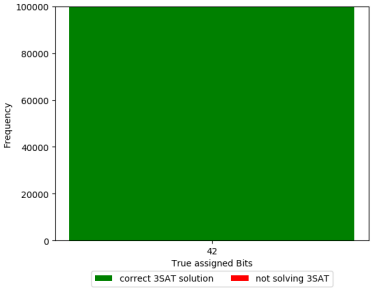
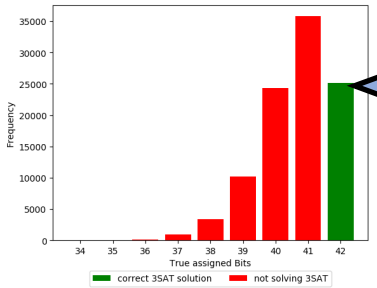




≈ 25% precision

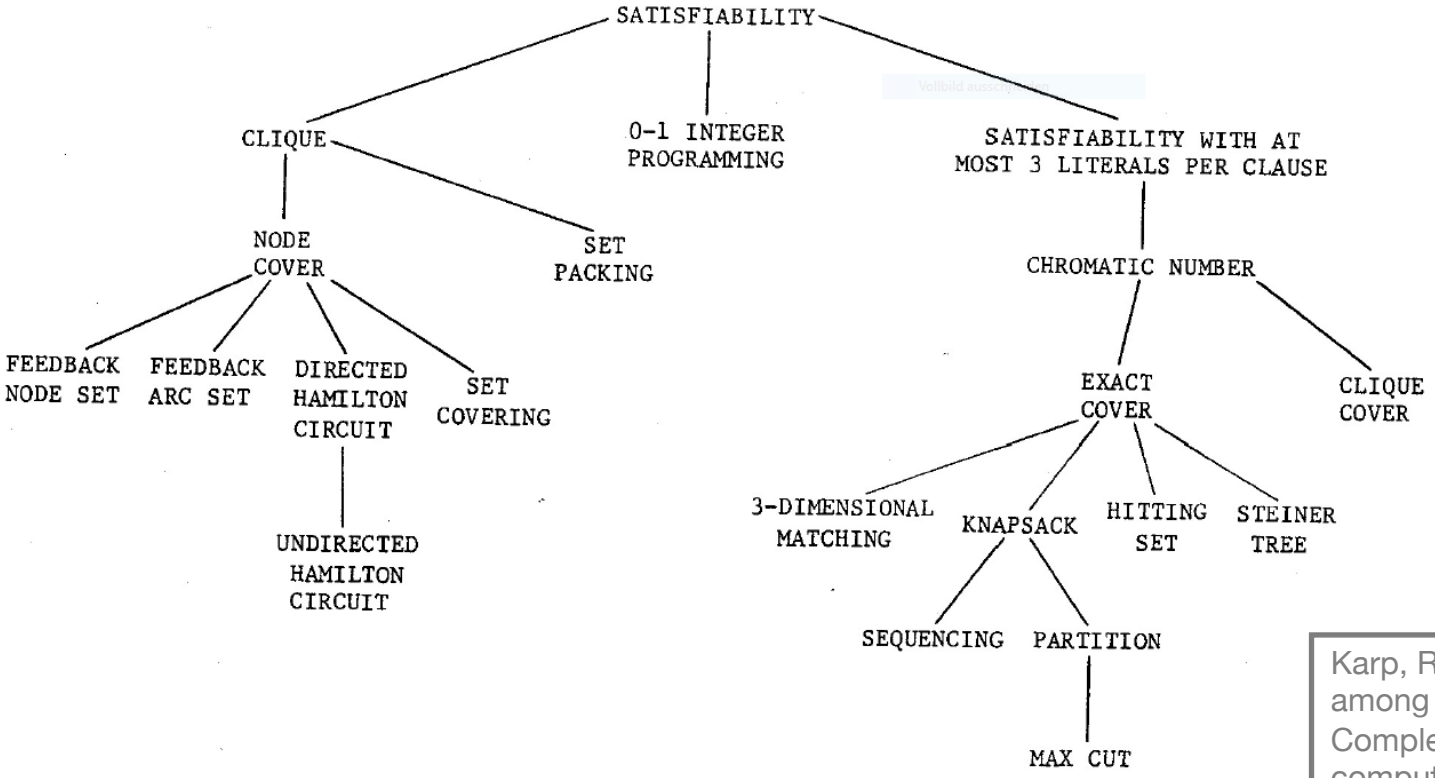
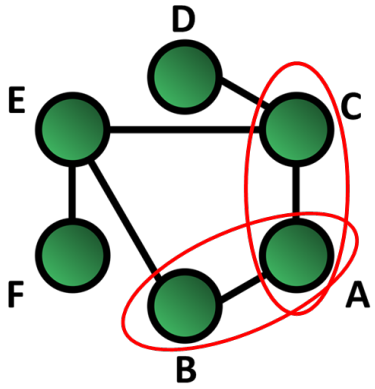


FIGURE 1 - Complete Problems

Karp, Richard M. "Reducibility among combinatorial problems." Complexity of computer computations. Springer, Boston, MA, 1972. 85-103.

Q-Nash

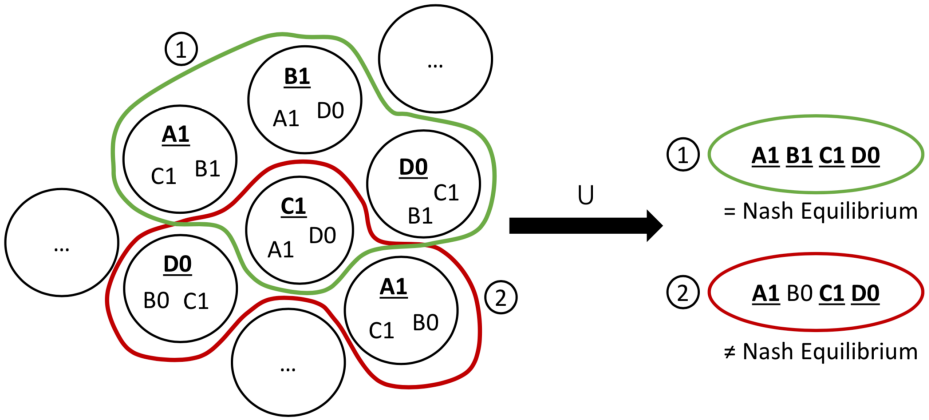


- Given a graphical game
  - players are nodes, interactions are edges
  - players only play a game with their neighbors
- What joint action is a pure Nash equilibrium?
  - no player can improve by deviating from joint action unilaterally

Roch, C., Phan, T., Feld, S., Müller, R., Gabor, T., & Linnhoff-Popien, C. (2019). A Quantum Annealing Algorithm for Finding Pure Nash Equilibria in Graphical Games. arXiv preprint arXiv:1903.06454.

Step 1
Compute *best response strategies* for each player (classically)

Step 2
Reduce to Set Cover (run on Quantum Annealer)



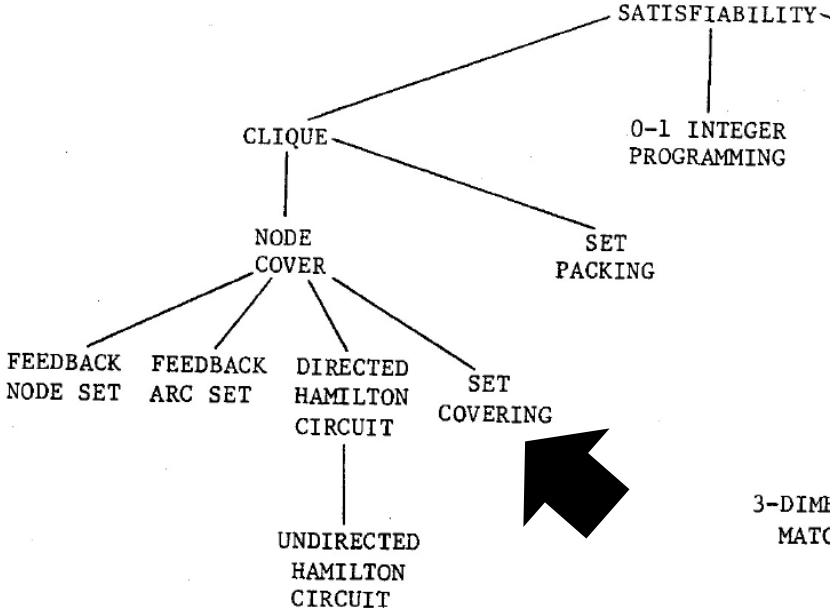
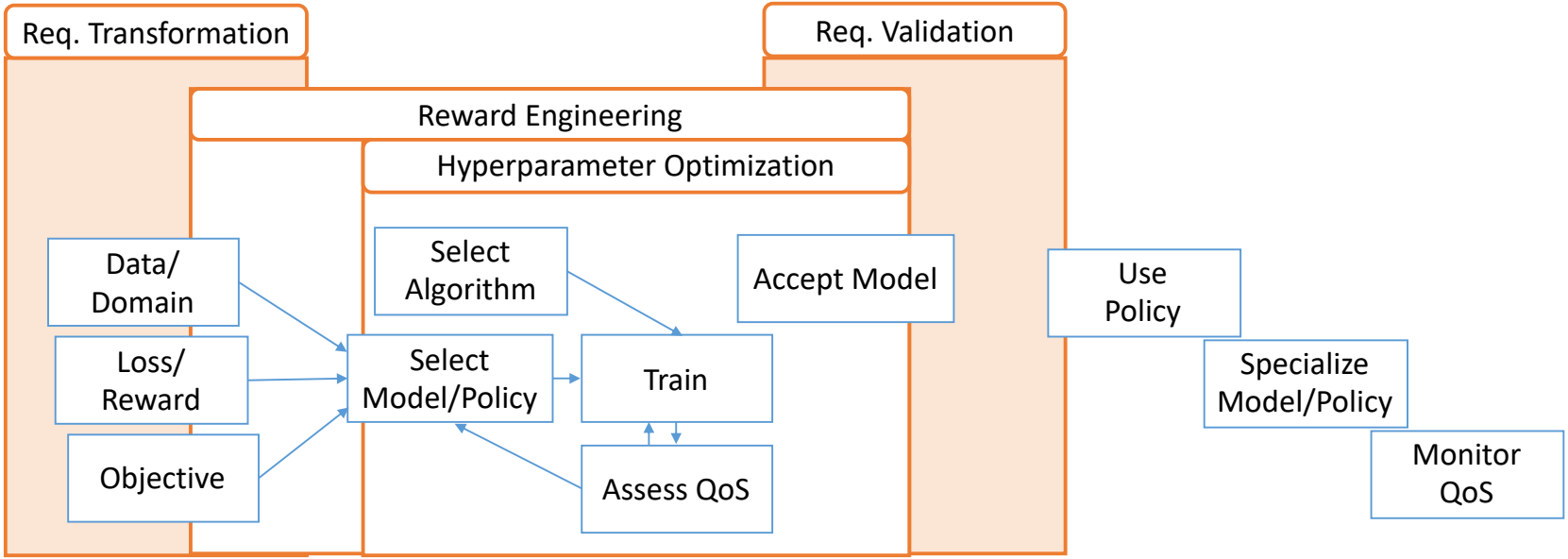


FIGURE 1 - Complete Pro

Machine Learning

Lenz Belzner et al.
Unpublished results.



Machine Learning

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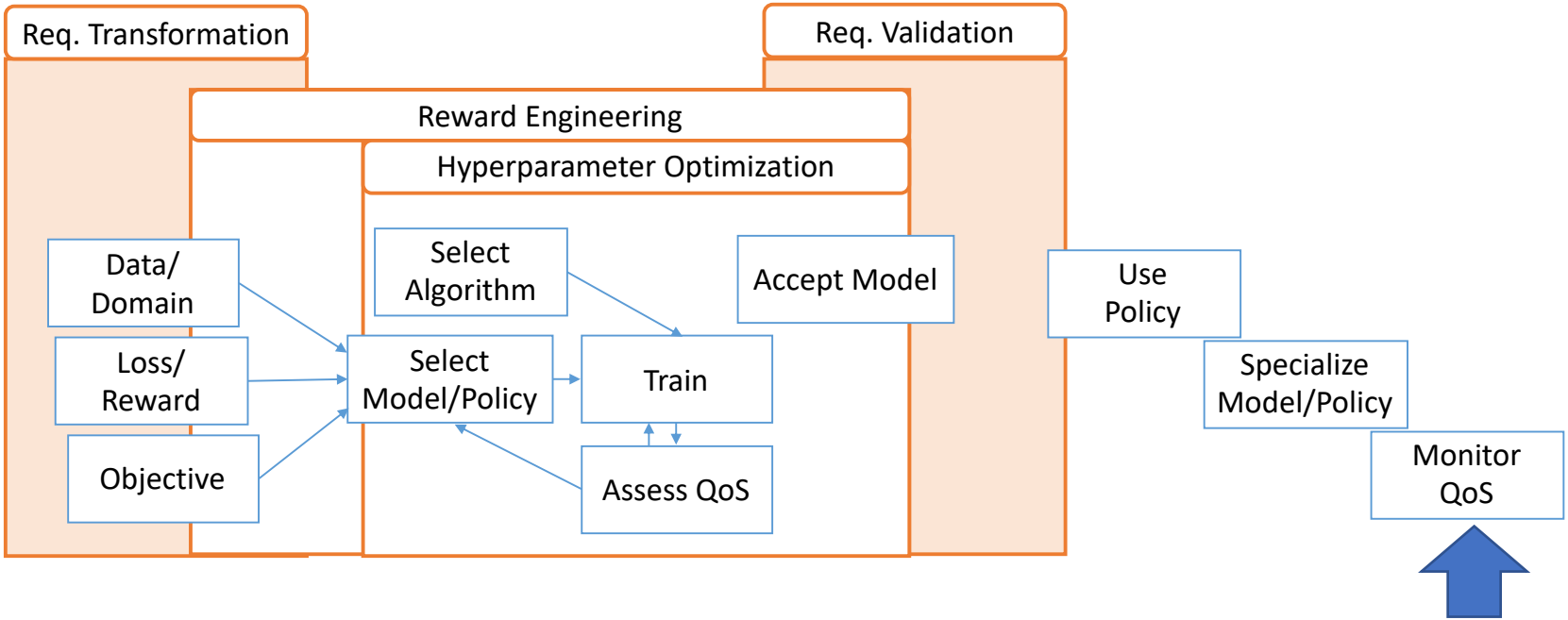
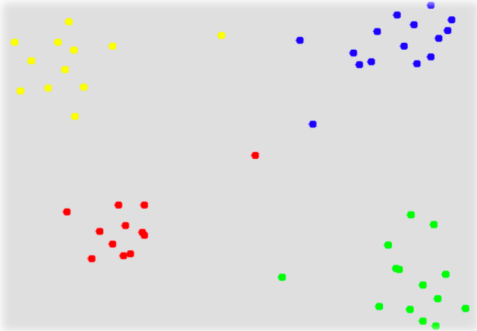


Monitoring QoS

Jonas Nüßlein
Unpublished results.

Jonas Nüßlein
"Most Frequent Itemset Optimization."
arXiv preprint arXiv:1904.07693 (2019).

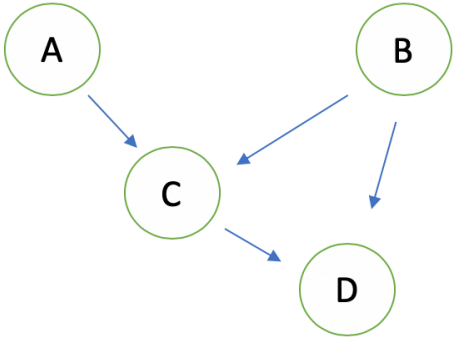
Clustering



Frequent Itemset Mining

AG, AC, GD, CF, DB, FB, BD
CF, EB, FB, BE, BA, EC
EE, DC, EA, CA, AG, AB
AG, AC, GC, CE, CF, EE
BA, BA, AG, AC, GC, CF
GC, GA, CA, AB, AD, BE, DF

Bayesian Inference



Machine Learning

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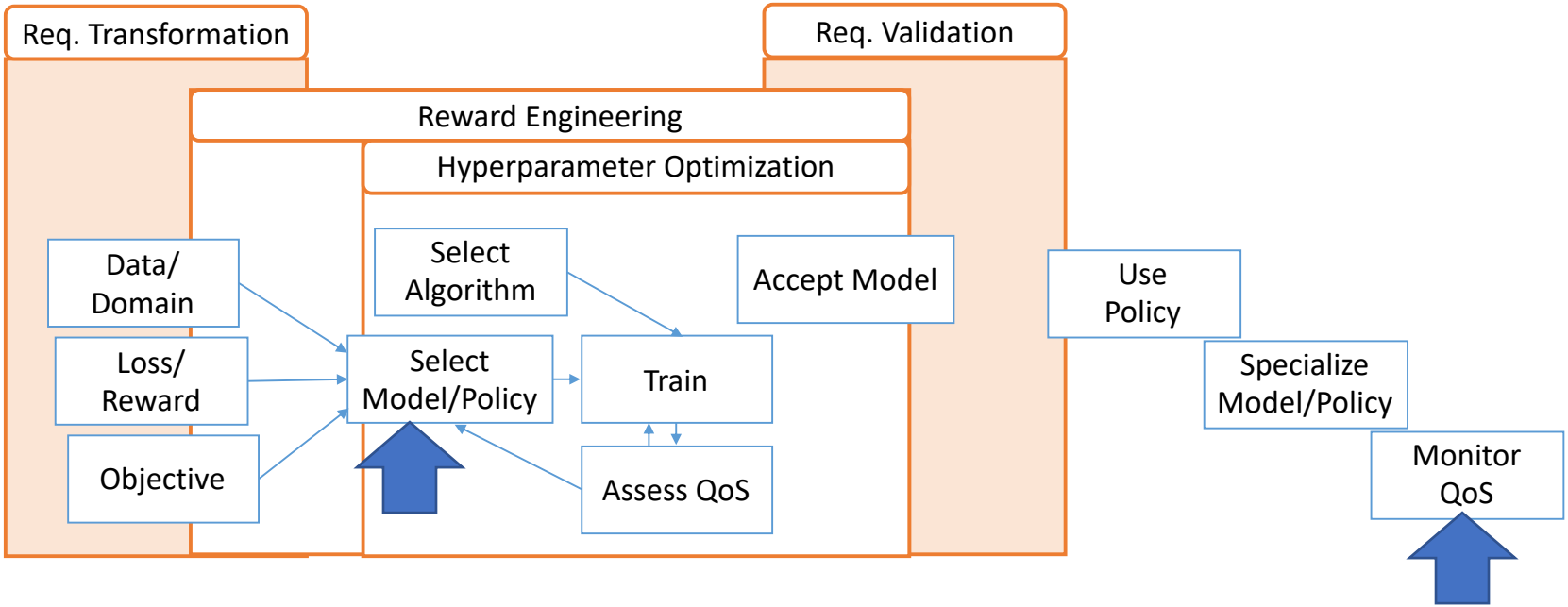


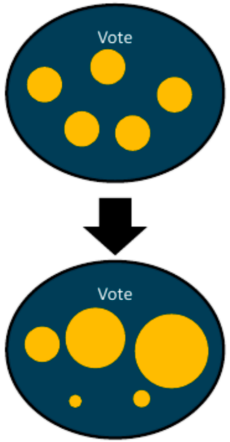
Select Model/Policy

H Neven, VS Denchev, G Rose, WG Macready. QBoost: Large Scale Classifier Training with Adiabatic Quantum Optimization. ACML, 2012.

Andreas Hessenberger. Unpublished results.

Florian Neukart, David Von Dollen, Christian Seidel, Gabriele Compostella. Quantum-Enhanced Reinforcement Learning for Finite-Episode Games with Discrete State Spaces. Frontiers in Physics 5, 2017.

Classifier Selection (QBoost)



Sample Selection (Quantum-Enhanced Q-Learning)

$$QUBO(i,j) = \begin{cases} QUBO(i,j) + (L_{i(v)} + L_{j(v)})^2, & \text{if c1} \\ QUBO(i,j) - ((L_{i(v)} + L_{j(v)})^2), & \text{if c2} \\ QUBO(i,j), & \text{otherwise} \end{cases}$$

Machine Learning

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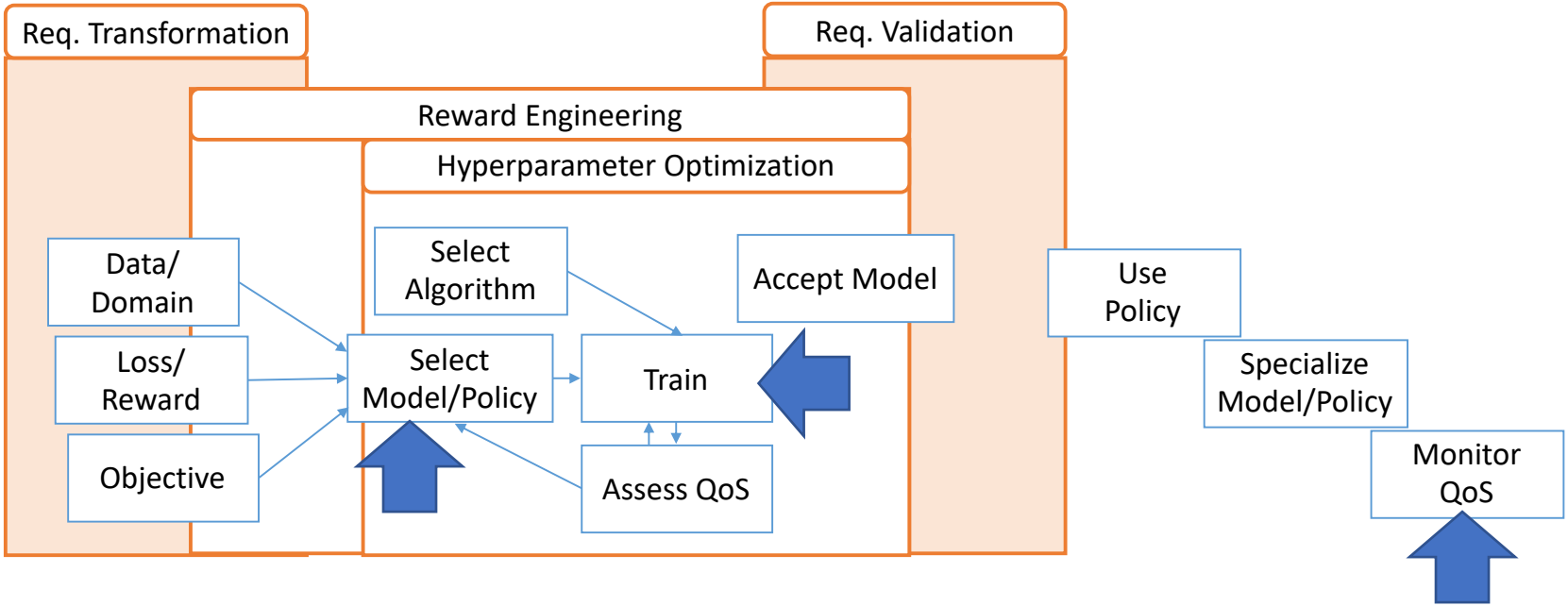
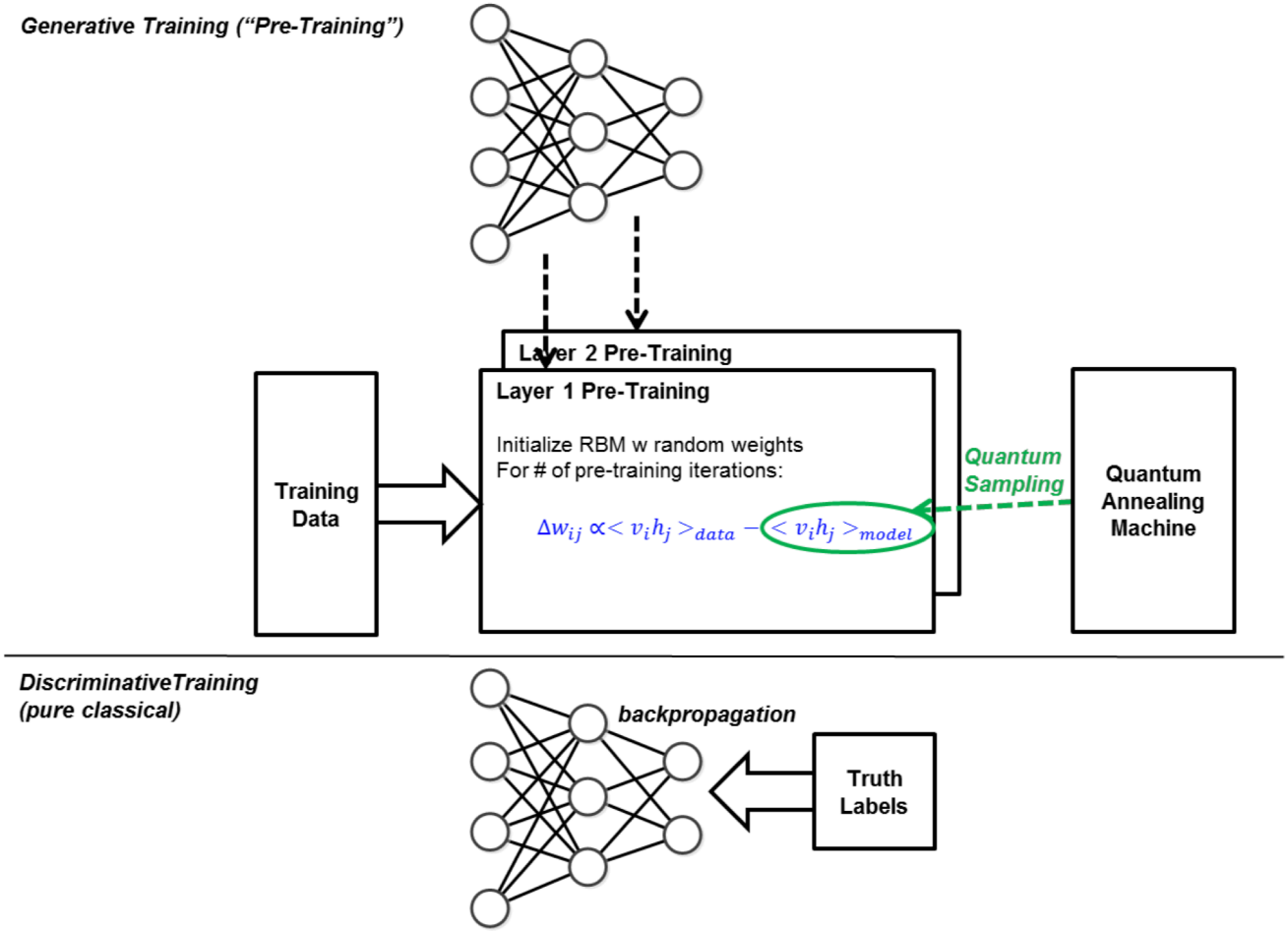


Train

Steven H. Adachi, Maxwell P. Henderson
Application of Quantum Annealing to Training of Deep Neural Networks.
arxiv.org/abs/1510.06356



Machine Learning

Lenz Belzner et al.
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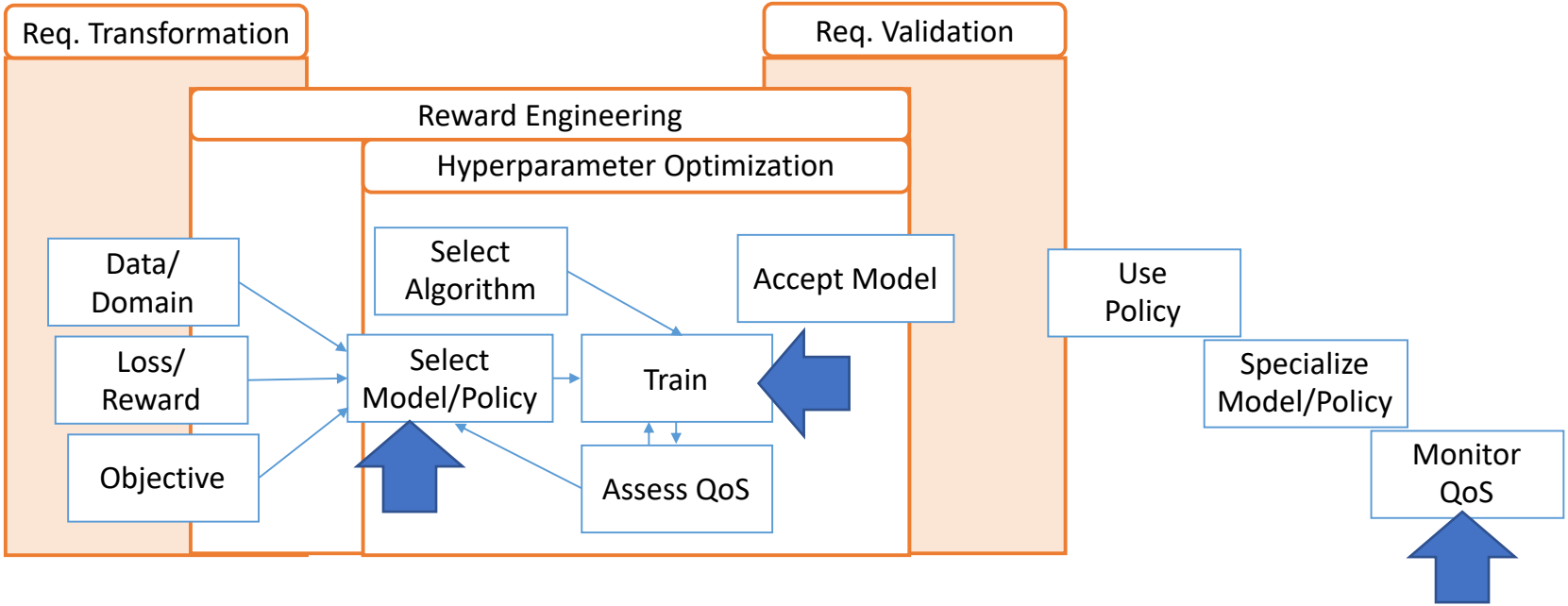

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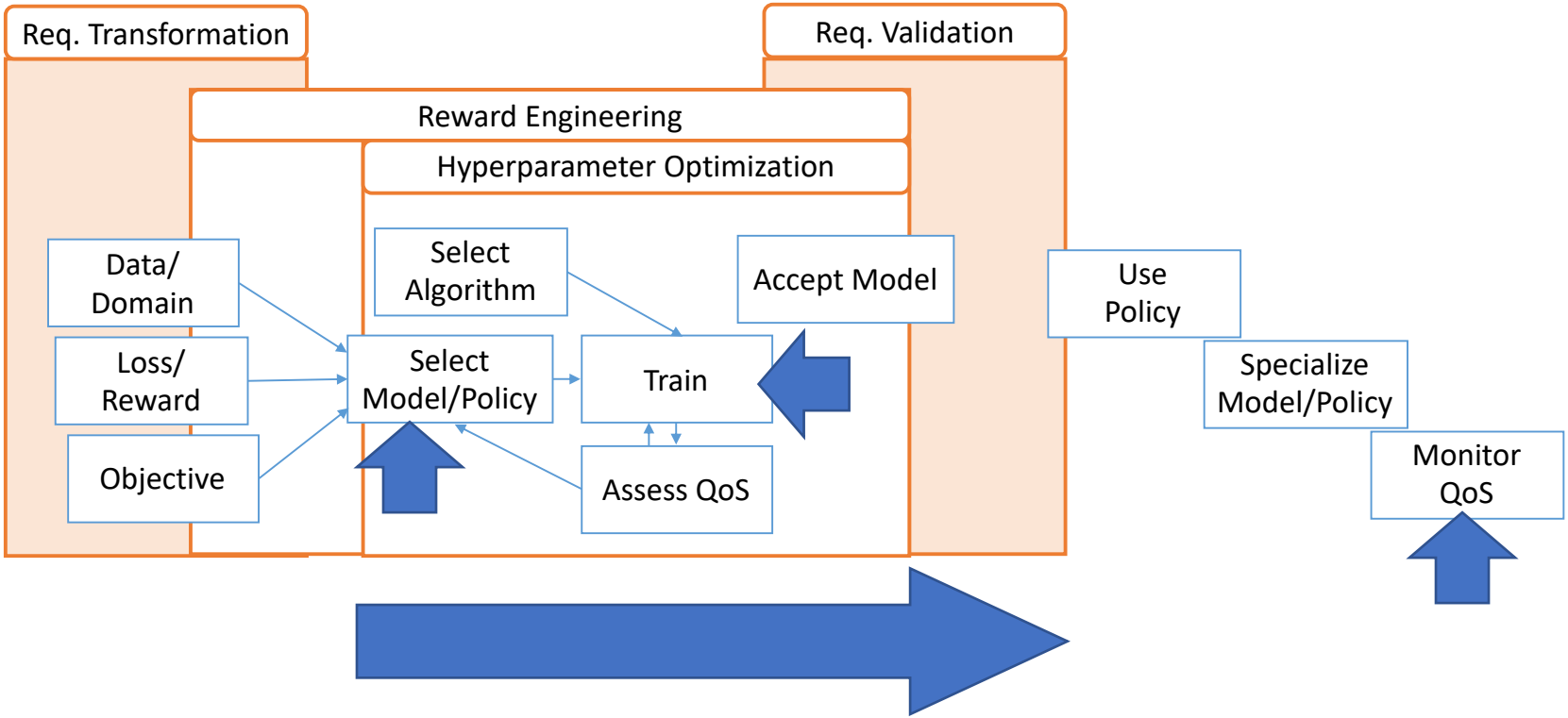

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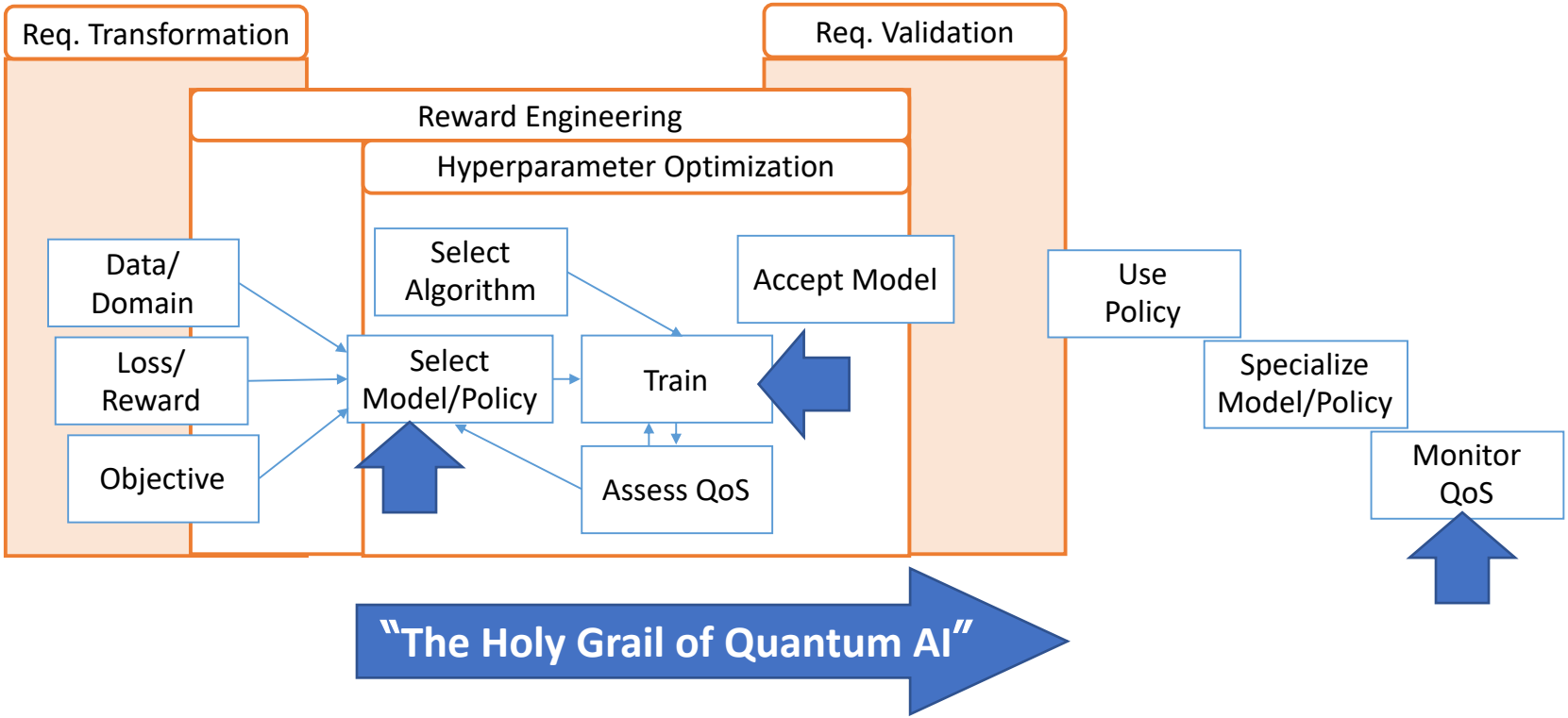

logo under
construction

PlanQK Initiative

PlanQK

Plattform und Ökosystem für Quantenunterstützte Künstliche Intelligenz

platform and ecosystem for quantum-supported artificial intelligence

Universität Stuttgart

Why further complicate AI?

AI and Computation

1) "AI researchers have often tried to **build knowledge** into their agents,
2) this always helps in the **short term**, and is personally satisfying to the researcher, but
3) in the long run it plateaus and even **inhibits further progress**, and
4) breakthrough progress eventually arrives by an opposing approach based on scaling computation by **search and learning**."

Rich Sutton.
The Bitter Lesson.
www.incompleteideas.net/IncIdeas/BitterLesson.html

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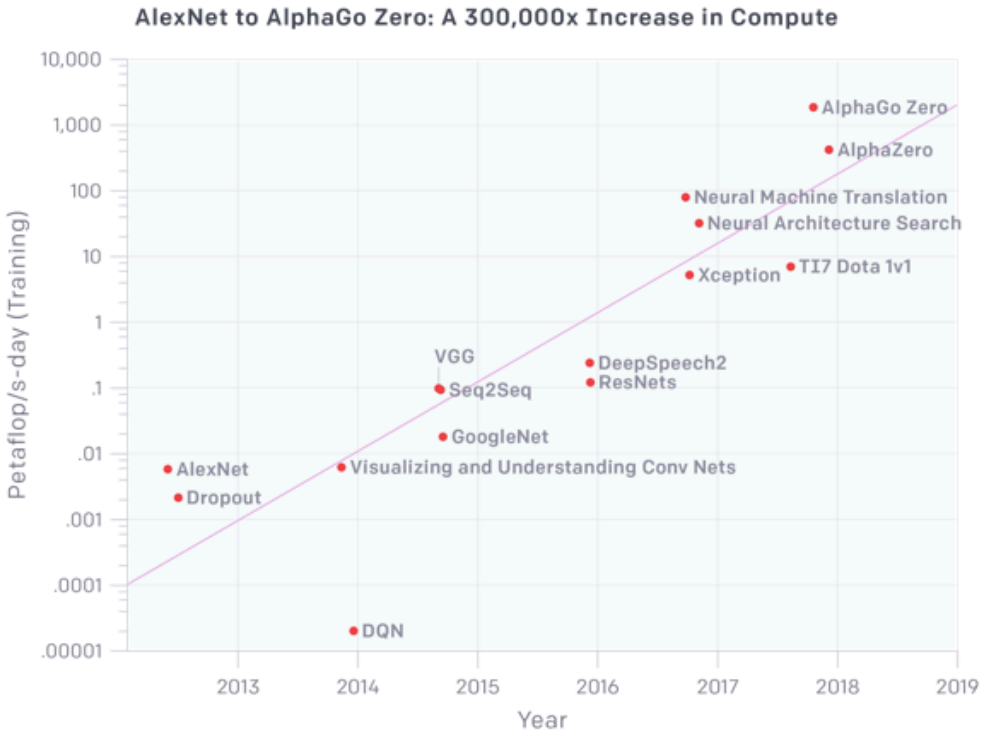
4) breakthrough progress eventually arrives by an opposing approach based on scaling computation by **search and learning**."

"The biggest lesson that can be read from 70 years of AI research is that general methods that **leverage computation** are ultimately the most effective, and by a large margin."

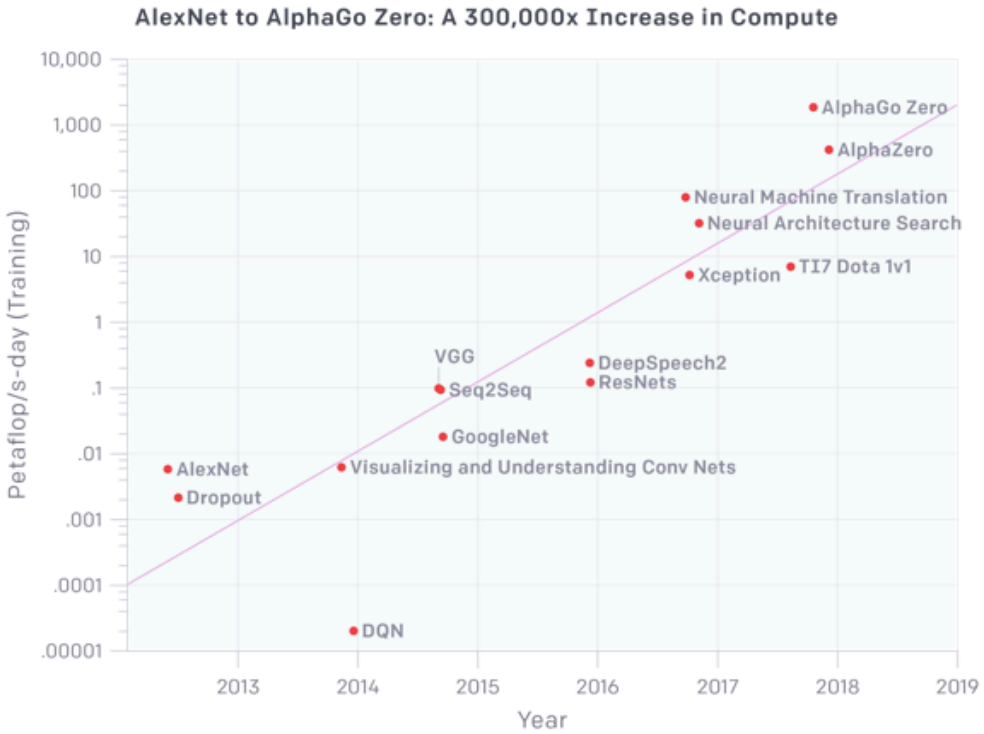
Rich Sutton.
The Bitter Lesson.
www.incompleteideas.net/IncIdeas/BitterLesson.html

Computation Power used in AI



Dario Amodei and Danny Hernandez.
AI and Compute.
openai.com/blog/ai-and-compute/

Computation Power used in AI



"Since 2012, the amount of compute used in the largest AI training runs has been increasing exponentially with a **3.5 month doubling time** (by comparison, Moore's Law had an 18 month doubling period)."

Dario Amodei and Danny Hernandez. AI and Compute. openai.com/blog/ai-and-compute/

Options for the Future

Options for the Future

AI experiments become more expensive

Options for the Future

AI experiments become more expensive

Progress in AI research slows down

Options for the Future

AI experiments become more expensive

Progress in AI research slows down

We find a way to increase available computing power

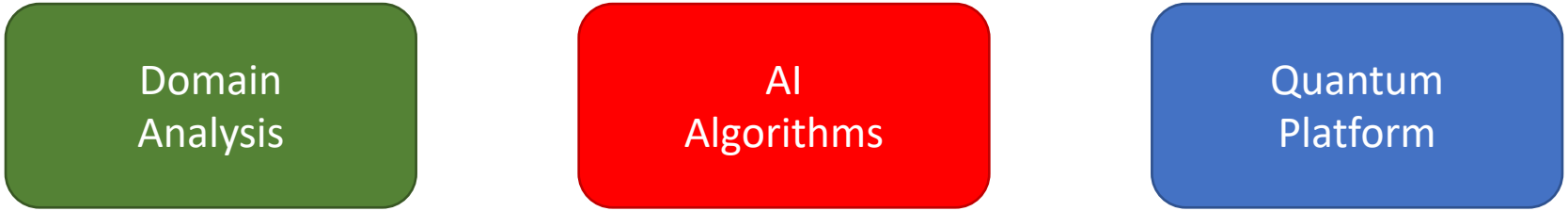
Options for the Future

AI experiments become more expensive

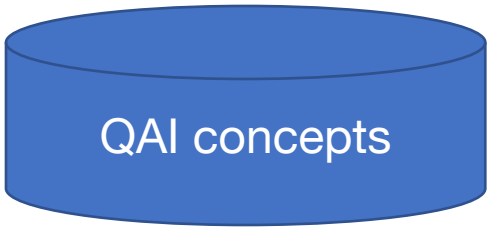
Progress in AI research slows down

We find a way to increase available computing power

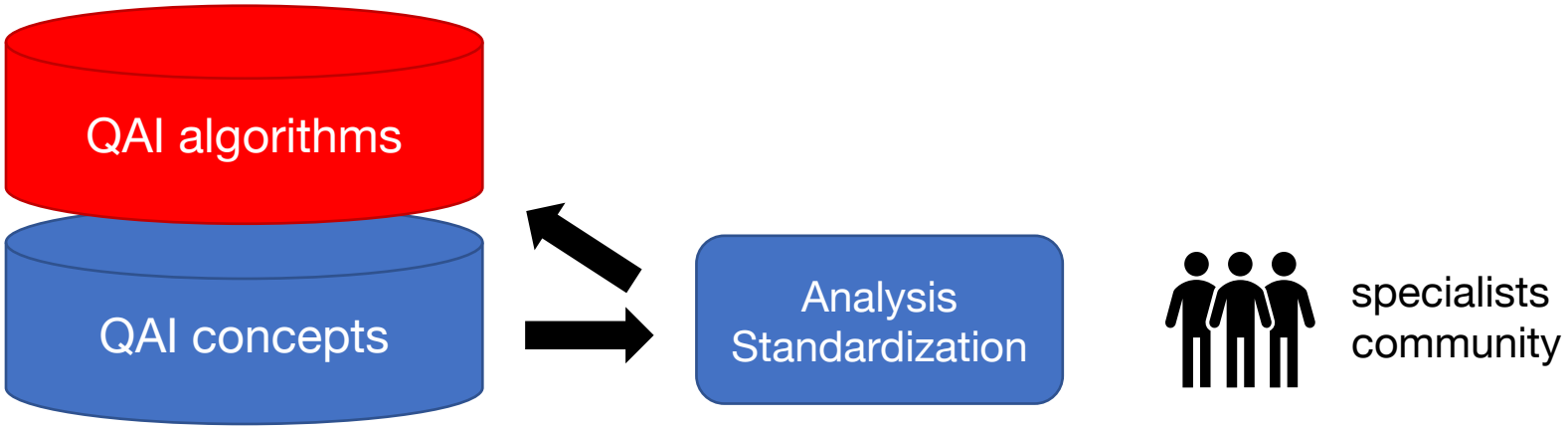
An Awful Lot of Expertise



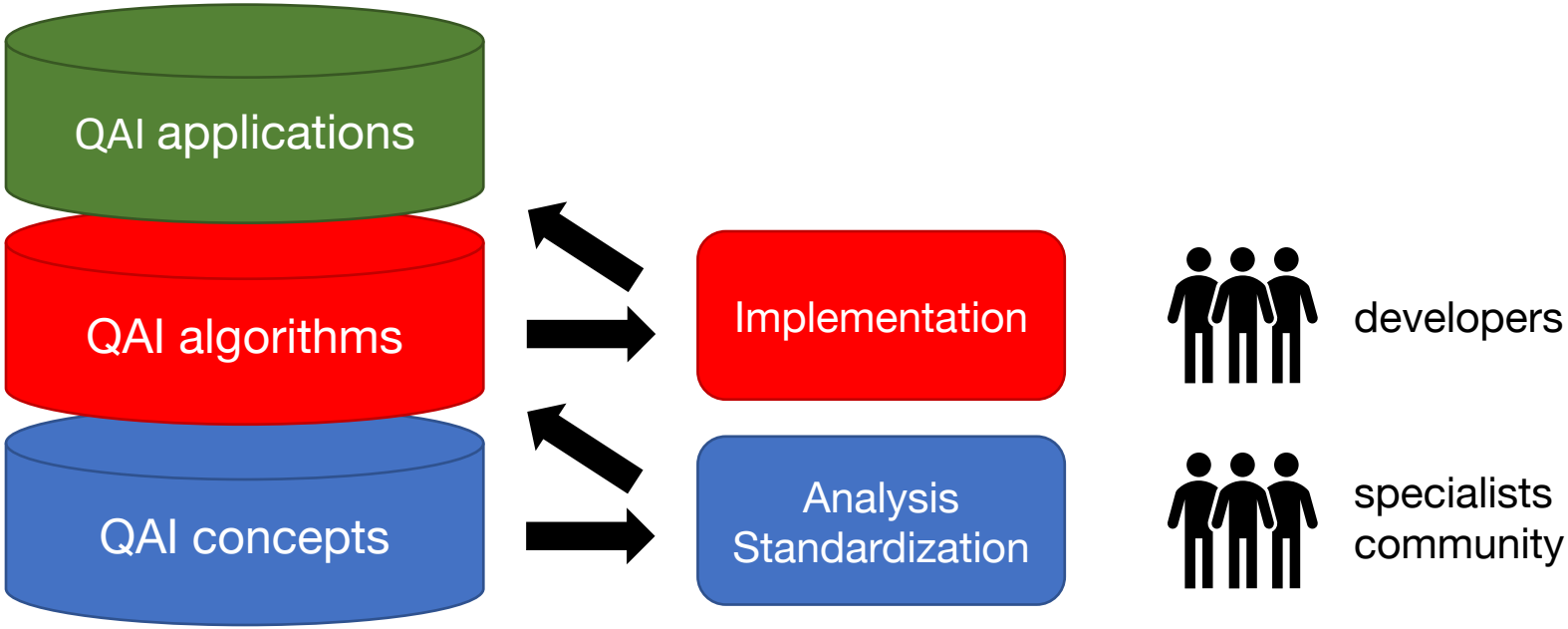
PlanQK



PlanQK


QAI algorithms
QAI concepts
Analysis
Standardization
specialists
community

PlanQK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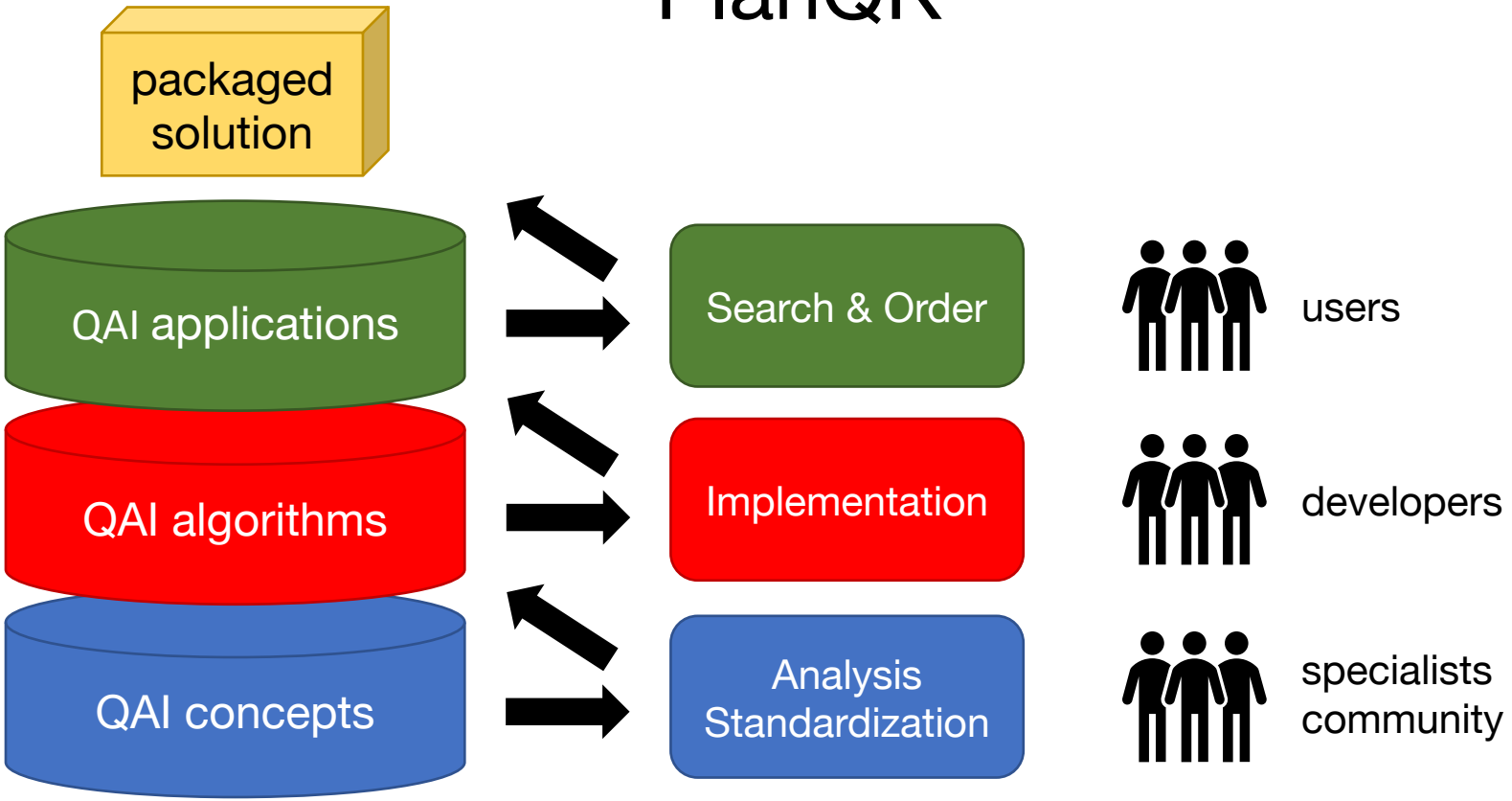
packaged solution
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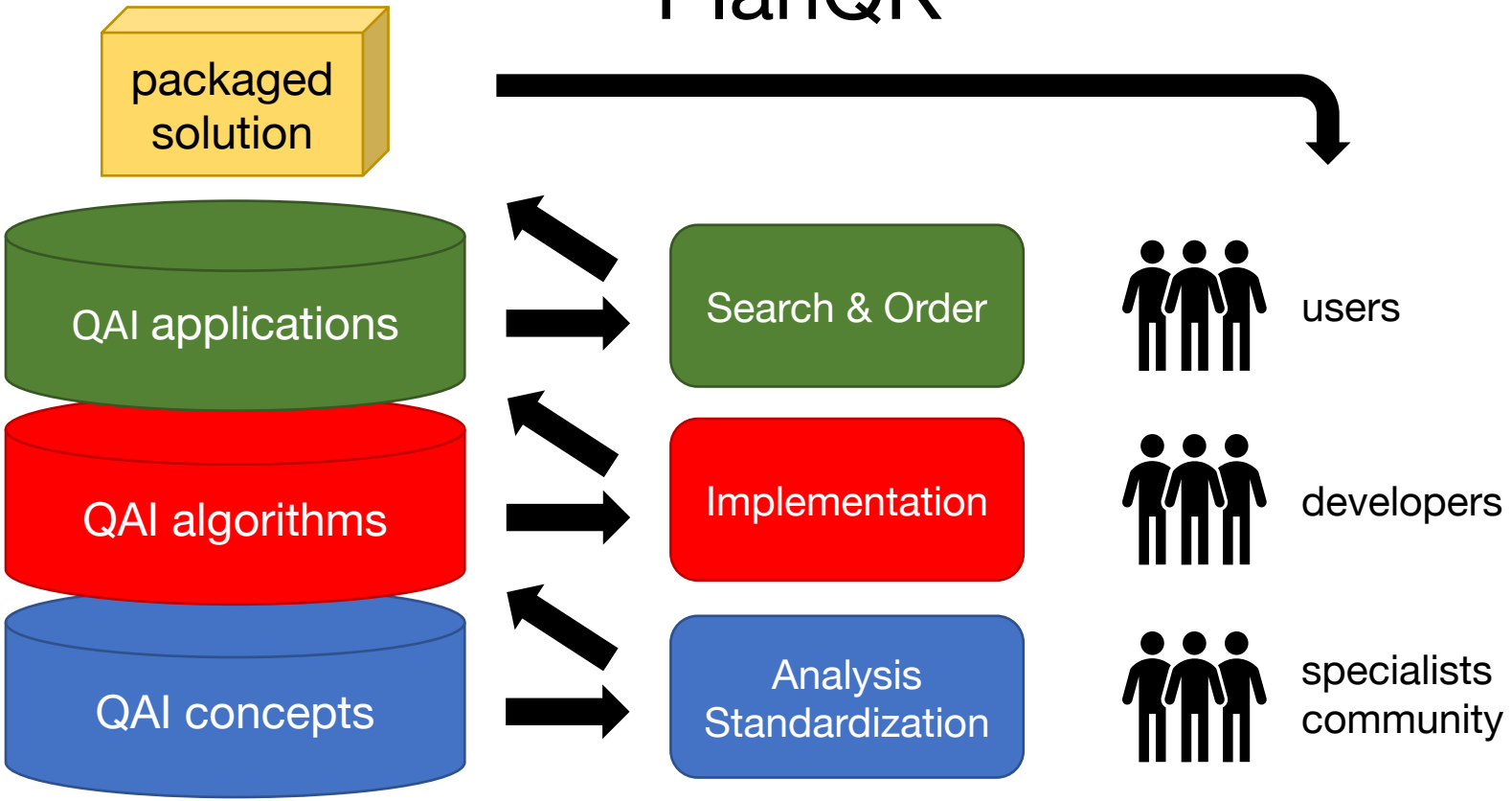
PlanQK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The Plan for PlanQK

We are preparing a roadmap for making PlanQK reality.

The Plan for PlanQK

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funded by the German ministry for commerce (BMWi)

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describing a larger follow-up project with many more partners (including you?)

The Plan for PlanQK

also funded by the BMWi?

We are preparing a roadmap for making PlanQK reality.

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describing a larger follow-up project with many more partners (including you?)

The Plan for PlanQK

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HQS QUANTUM SIMULATIONS

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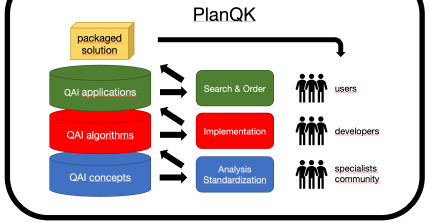

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near-term

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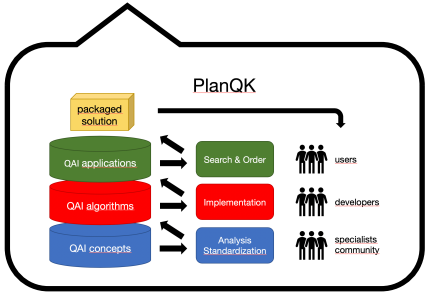

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QAR-Lab

For more information ask me!

or visit

www.mobile.ifi.lmu.de/qar-lab

www.mobile.ifi.lmu.de/planqk

or both

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