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Quantum Optimization: current trends and open opportunities

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POLIMI
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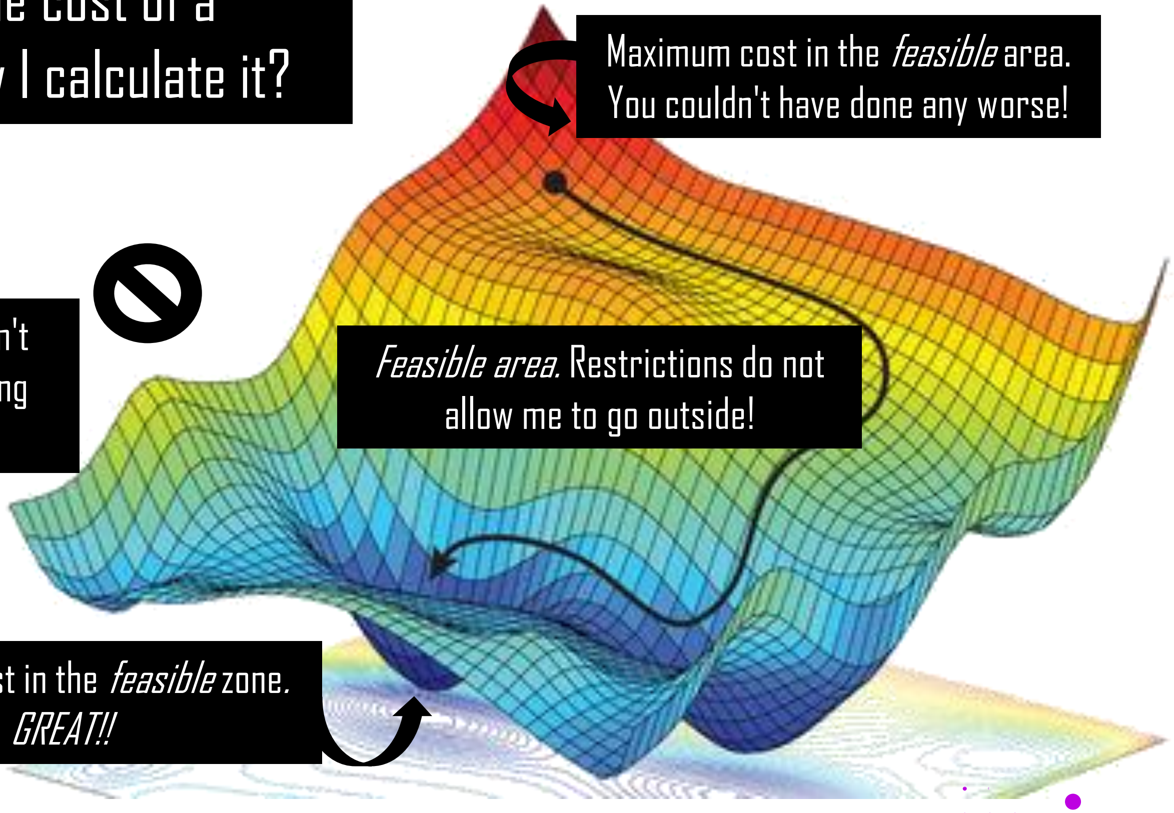
Optimization

Real Problem:
Minimize the cost of a route. ¿How I calculate it?

→ **Computational problem / Technique : Optimization**



Maximum cost in the *feasible* area. You couldn't have done any worse!

Unfeasible zone. Don't send me to the wrong address to drive!

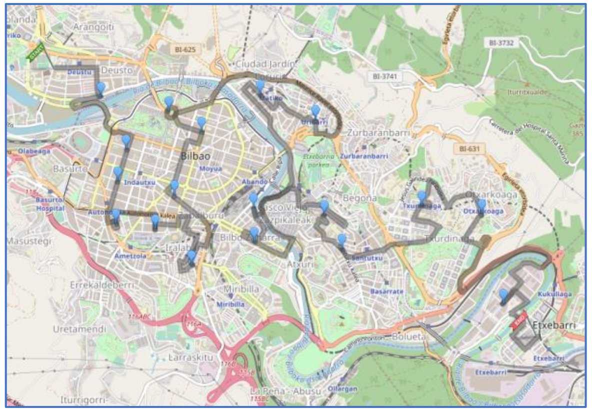
Feasible area. Restrictions do not allow me to go outside!

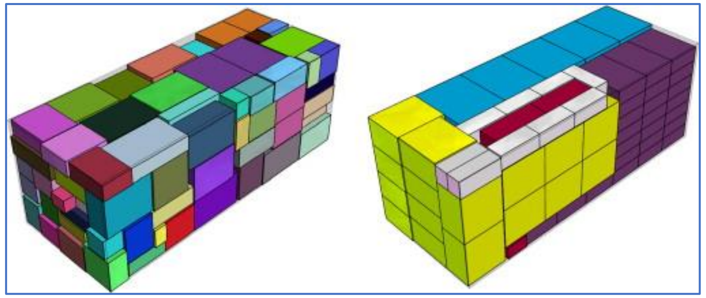
Minimum cost in the *feasible* zone. *GREAT!!*

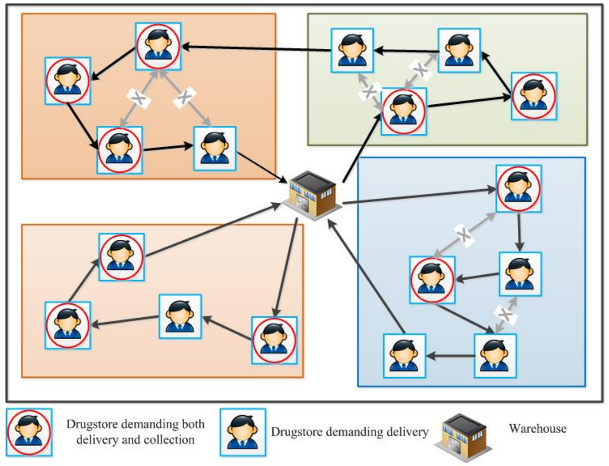
KEY CONCEPTS:

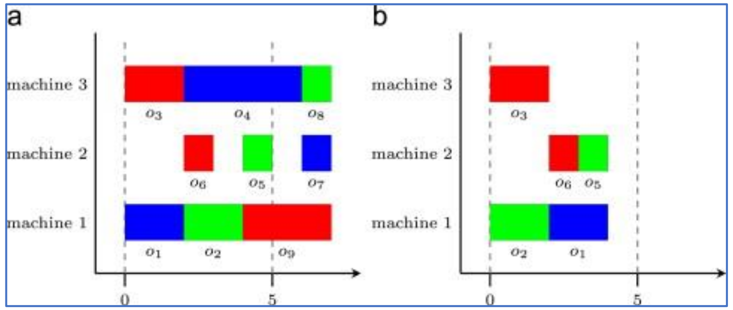
- We always seek to minimize (or maximize) something that we can measure in some way (e.g. cost of gasoline).
  → **Objective function (a.k.a. fitness).**
- This maximization depends on variables whose value we must "vary" intelligently to find the one that leads to the minimum/maximum of the objective function.(e.g. paths).
  → **Decision variables.**
- We cannot just give any value to the decision variables. We have to move through specific zones.
  → **Restrictions imposing feasibility.**
- Intelligent optimization consists of designing algorithms that **efficiently** search for the optimal value of decision variables while respecting the constraints.

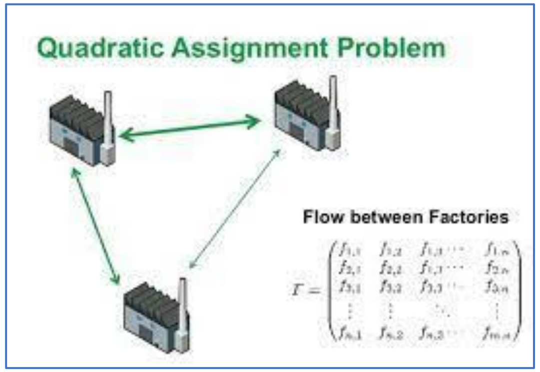
Problem examples











Quantum Optimization

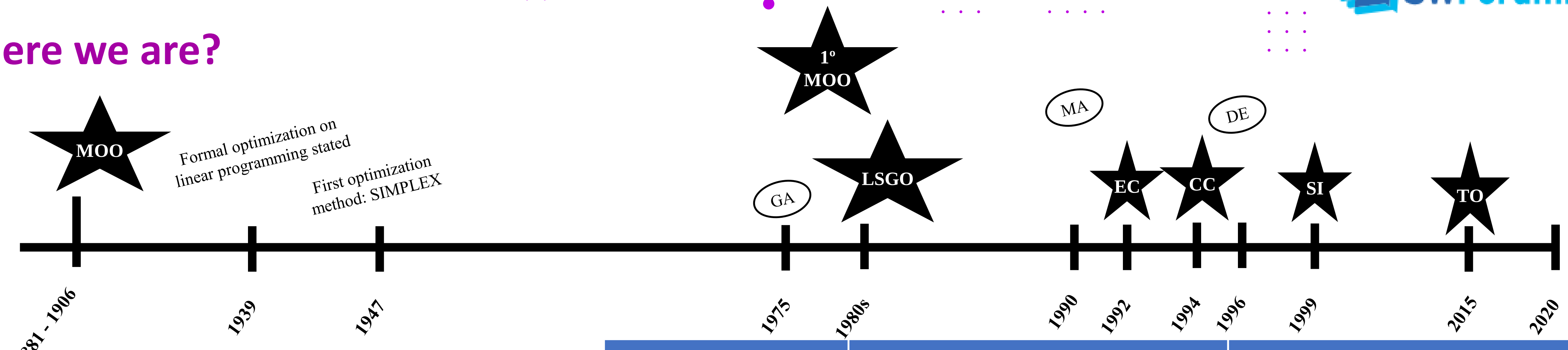
- **Quantum optimization** has generated a profound impact in recent years → the **fast advances** in hardware technology and the **democratization of its access** have made research take off.

- How to **implement novel quantum solvers** or how **to introduce quantum methods into already-existing classical pipelines** is currently attracting great interest.

- **Application fields**: transportation, finance, energy, or medicine.

Quantum computing paradigms

Where we are?



D:WAVE
The Quantum Computing Company™

- 1999 — D-WAVE is found
- 2007 — First prototype:
- 2011 — D-WAVE ONE (1
- 2013 — D-WAVE TWO (512 qubit)
- 2015 — D-WAVE 2X (+1000 qubit)
- 2017 — D-WAVE 2000Q (2048 qubit)
- 2018 — D-WAVE LEAP — “democratization” in the access
- 2020 — Advantage_system1.1 (5616 qubit)

Application field	Quantum Computing	Classic Computing
		Robotic applications in herding, in environments of 2.5 hectares and a flock of 30 sheep.
		Multi-TSP with drones (50 nodes). Swarm Intelligence methods able to solve instances of 85.000 nodes in less than an hour, and algorithms solving 1002-noded instances in 14 seconds with an error less than 1%.
	approaches and a maximum of 415 cars.	For the same problem, NASA published a study with over 2500 aircraft, weather conditions and other constraints in 2009.
Industry	First JSP formulations and proofs of concept with up to 6 tasks and 6 machines.	Hybrid methods based on evolutionary computation for the flexible and fuzzy variant of JSP, solving 30-task and 15-machine instances.
Finance	Hybrid methods for solving the portfolio optimization problema with up to 60 stock to invest, with a limited granularity of investment.	Predict the collapse of the oil sector with data on the price of oil, gold, sugar, cocoa, stock market related indices... with a depth of 1000 days.

Processor:	2000Q	Advantage	Advantage2 Prototype	Advantage2
Status	online	online	online	in development
Topology & grid size	Chimera C_{16}	Pegasus P_{16}	Zephyr Z_4	Zephyr Z_{15}
Qubits per unit cell	8	24	8	8
Couplers per qubit	6	15	20	20
Total qubits	> 2000	> 5000	563	> 7000
Total couplers	> 6000	$> 35,000$	4790	$> 60,000$

Quantum-classical hybrid solvers

- In the NISQ era, **quantum-classical solvers are receiving outstanding attention** from the community since they are arguably the near-term future in the context of quantum optimization and its application in real-world use cases.

- Hybrid approaches **are not just a way to circumvent the limited quantum resources** but a way of boosting performance in real-world use cases. Learning how to get the most out of each of them will be the key to success

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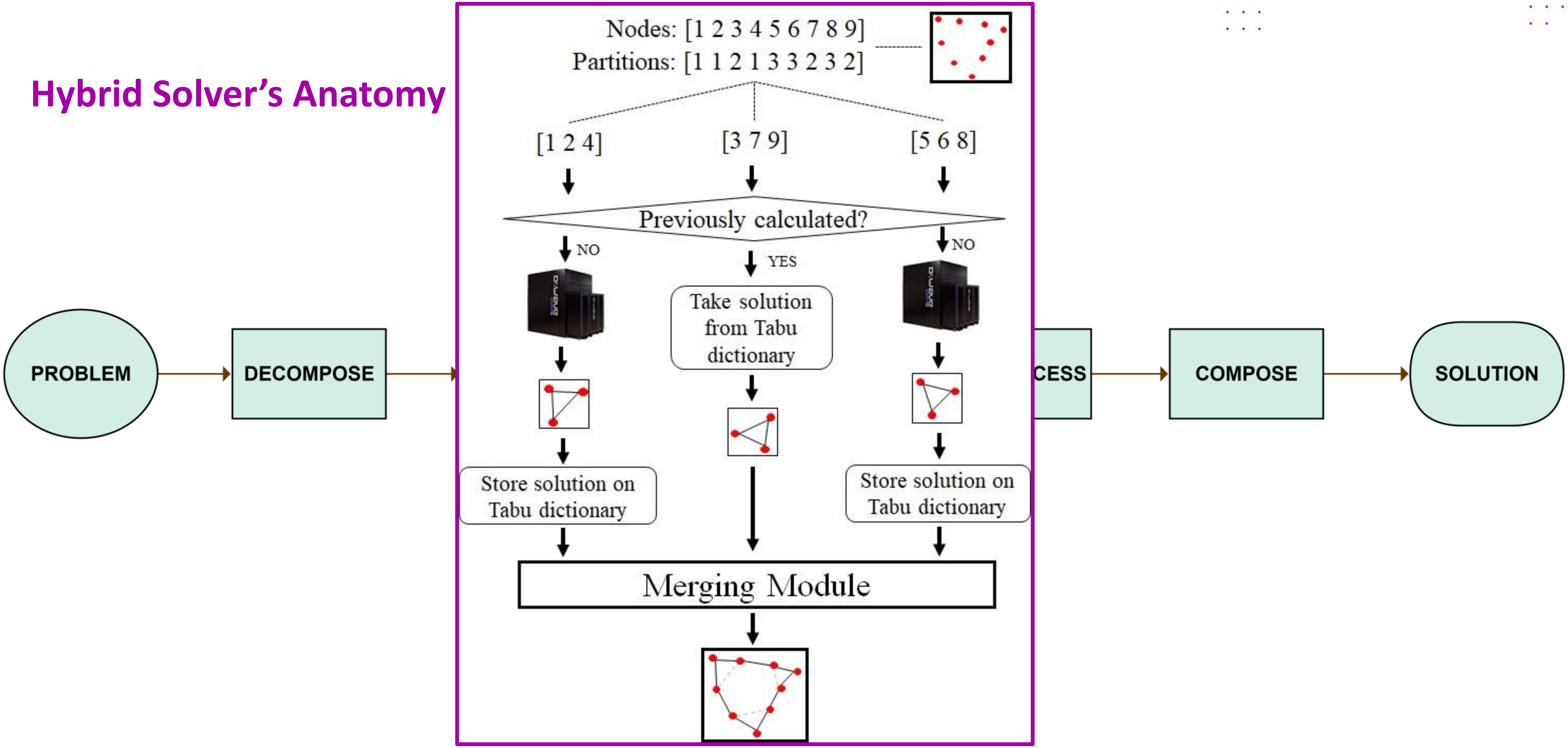
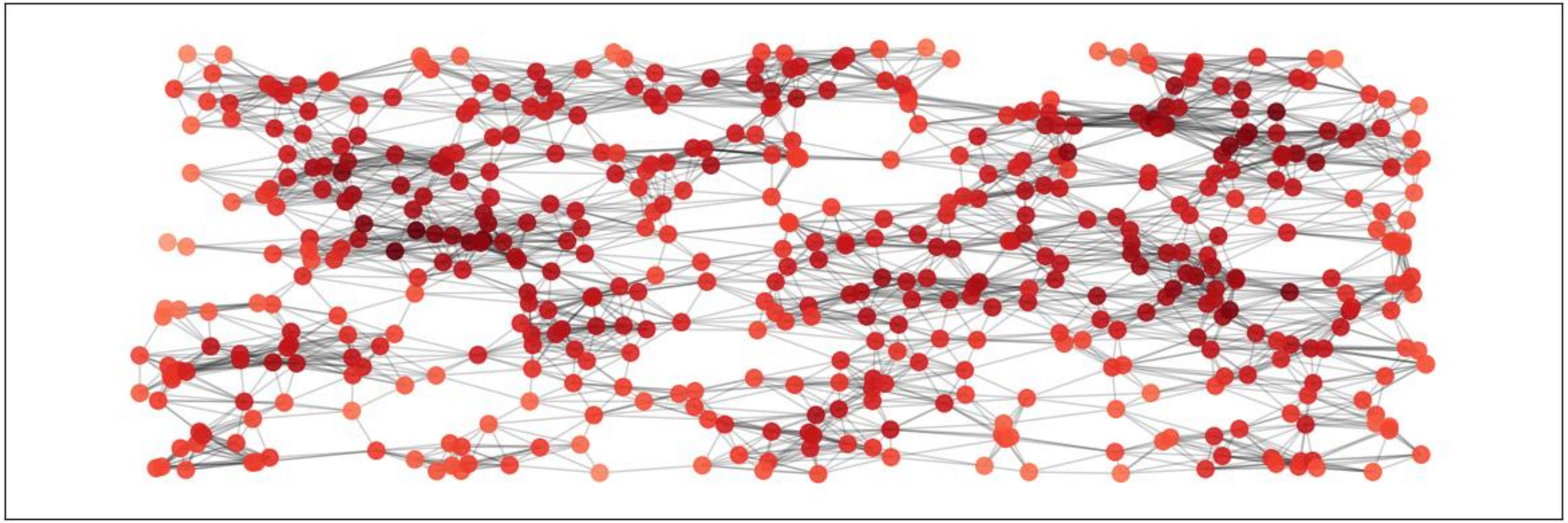
Hybrid Solver’s Anatomy

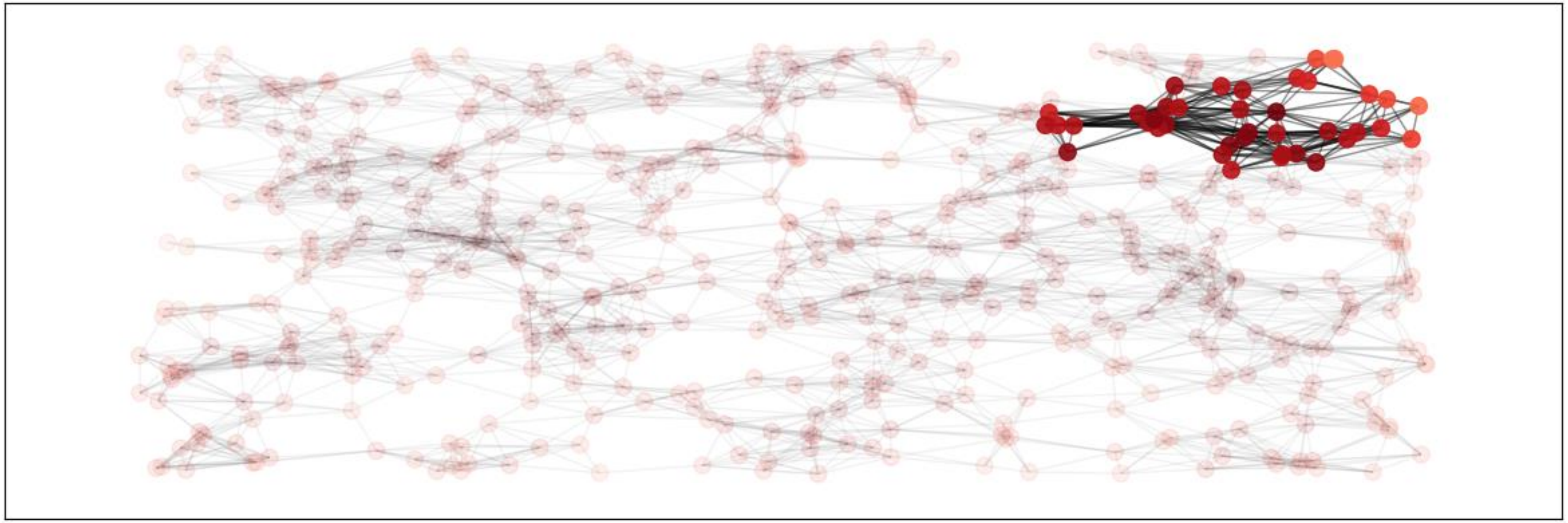


Decomposers



- Random Subproblem Decomposer
- Component Decomposer
- Energy Impact Decomposer

Decomposers / Energy Impact Decomposer



- Random Subproblem Decomposer
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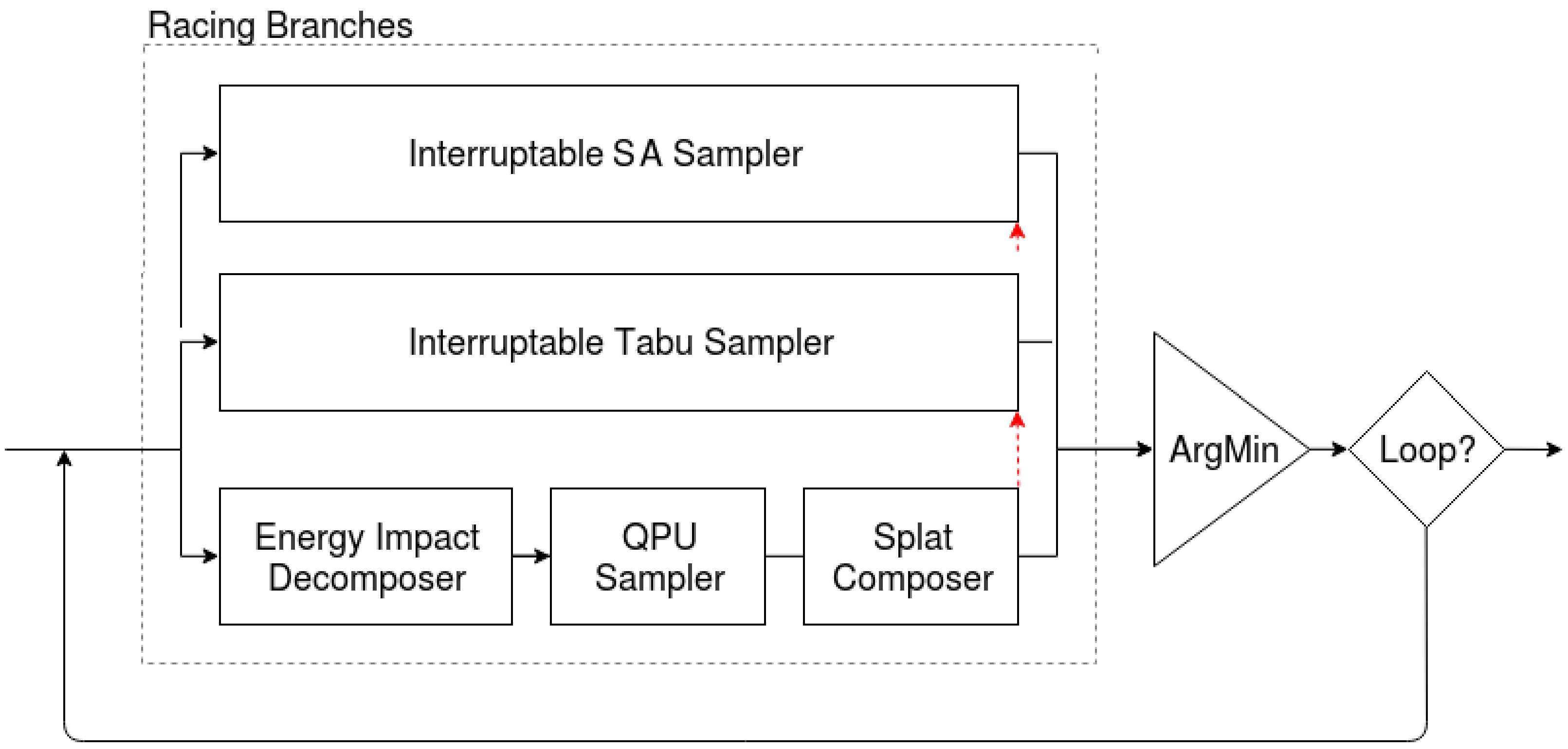
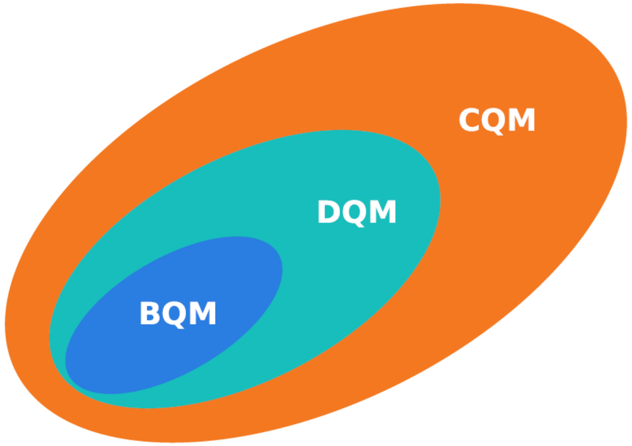
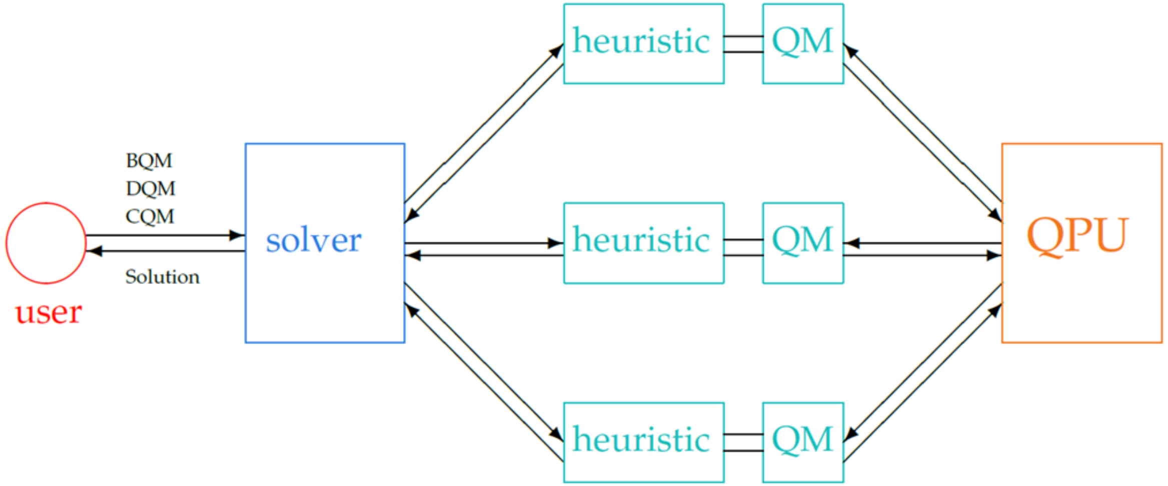
Hybrid Workflows (example of D-Wave's Kerberos)

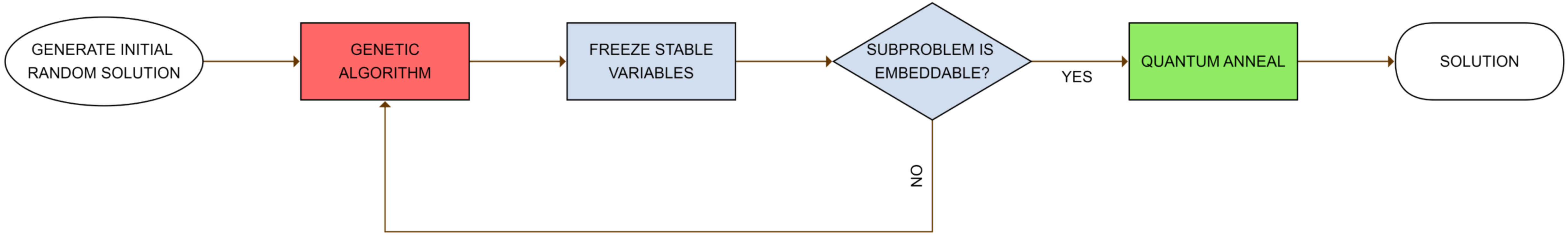


D-Wave Leap's Hybrid Solvers





Other alternatives: Freeze and Anneal



Current challenges related to the hybrid community

- Challenges coming from the **Talavera Manifesto**:
  - *Community should work on the proper communication among classical and quantum computing*: the classical and quantum methods must prove **own contributions in terms of non-trivial intelligence to be properly named hybrid**. This specification makes perfect sense since classical and quantum computing will be playing collaborative, not competitive, roles in the long-term horizon. As a step further, both would need to fuse their intelligence to be called as an imbricated solver.

  - *Researchers should consider the evolution of quantum software and hardware when developing hybrid methods*: practitioners should design and implement hybrid methods not only for overcoming current quantum devices limitations. Ideally, **algorithms developed should survive the noisy intermediate-scale quantum (NISQ) era** and be also effective in the upcoming fault-tolerant large-scale quantum era.

  - *Practitioners should develop techniques agnostic to any programming language and technologies*: NISQ era has led to an indissoluble partnership between quantum and classical computing, regardless the quantum paradigm employed. Researchers should elaborate on the design of **hybrid methods which quality do not depend on the programming language used in the classical part**. Also, hybrid solvers should be fully usable by both quantum-annealers and quantum gate-based devices.

Current challenges related to the hybrid community

- Quantum computing research community **holds complementary interests**, presumably as a result of individual areas of knowledge:

  - *Practitioners coming from industrial and applied research groups*, mostly concerned about quantum computing-based formulations and experiments over more realistic scenarios.

  - *Researchers coming from quantum physics*, usually interested in analyzing the hardware performance and reliability.

  - *Researchers with backgrounds in traditional artificial intelligence*, involved in testing the limits of QC, comparing results, and leveraging fundamentals, heuristics, or shareable-across-platform knowledge.

- One of the main challenges is **to build a united community and establish a strong research avenue**, which will lay the foundations that will guide research in the coming years. Only in this way can we survive the so-called **quantum winter**.

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