

the interplay between quantum science and quantum engineering



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QUEST-IS, EDF Palaiseau, December 1st, 2025

scientific development vs engineering

scientific development

engineering

goal

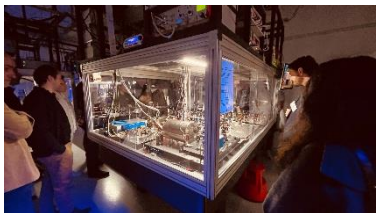
**discover or explain new
principles or phenomena**

**apply known principles and
science to solve practical problems**

scientific development vs engineering

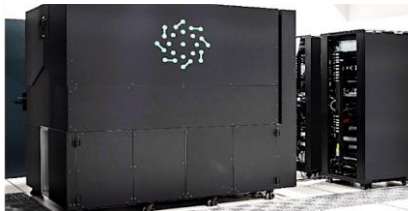
	scientific development	engineering
goal	discover or explain new principles or phenomena	apply known principles and science to solve practical problems
focus	understanding, modeling	designing, building, optimizing
methodology	hypothesis-driven, exploratory, small-scale experiments	constraint-driven, solution-oriented , design at practical scale
output	theories, models, fundamental bounds, proofs, experiments	devices, systems, processes, products
evaluation criteria	scientific validity, novelty , learnings, falsifiability	functionality , usefulness, efficiency, reliability, cost
time horizon	long-term, uncertain payoff	short-to-mid term, market-driven
economic constraints	variable, experimental setups	cost, manufacturability, user ROI

quantum engineering is a key enabler of the second quantum revolution



quantum science and research

- quantum physics
- condensed matter physics
- quantum photonics
- quantum cryptography
- quantum thermodynamics
- quantum metrology
- quantum information science



quantum technologies

- quantum computers
- quantum key distribution
- quantum networks
- quantum sensors
- quantum matter
- classical enabling technologies

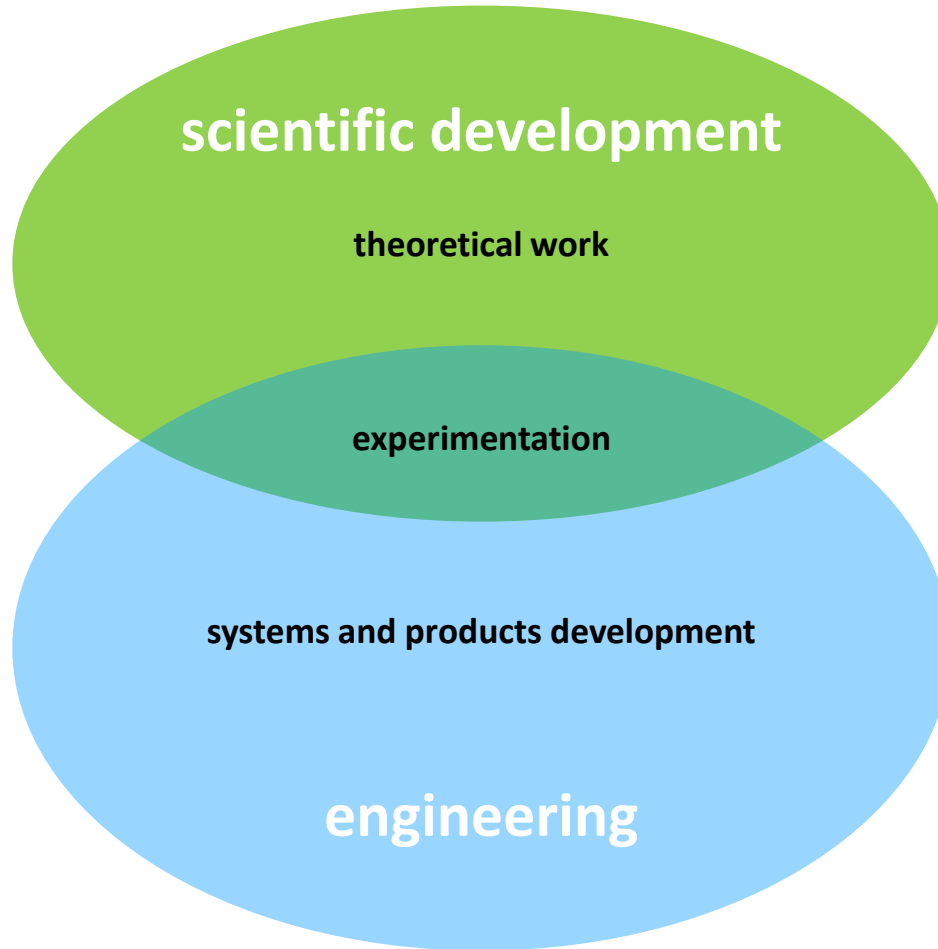


technology innovations

- products
- applications
- actual usage
- market outreach
- business and societal benefits
- economical impact

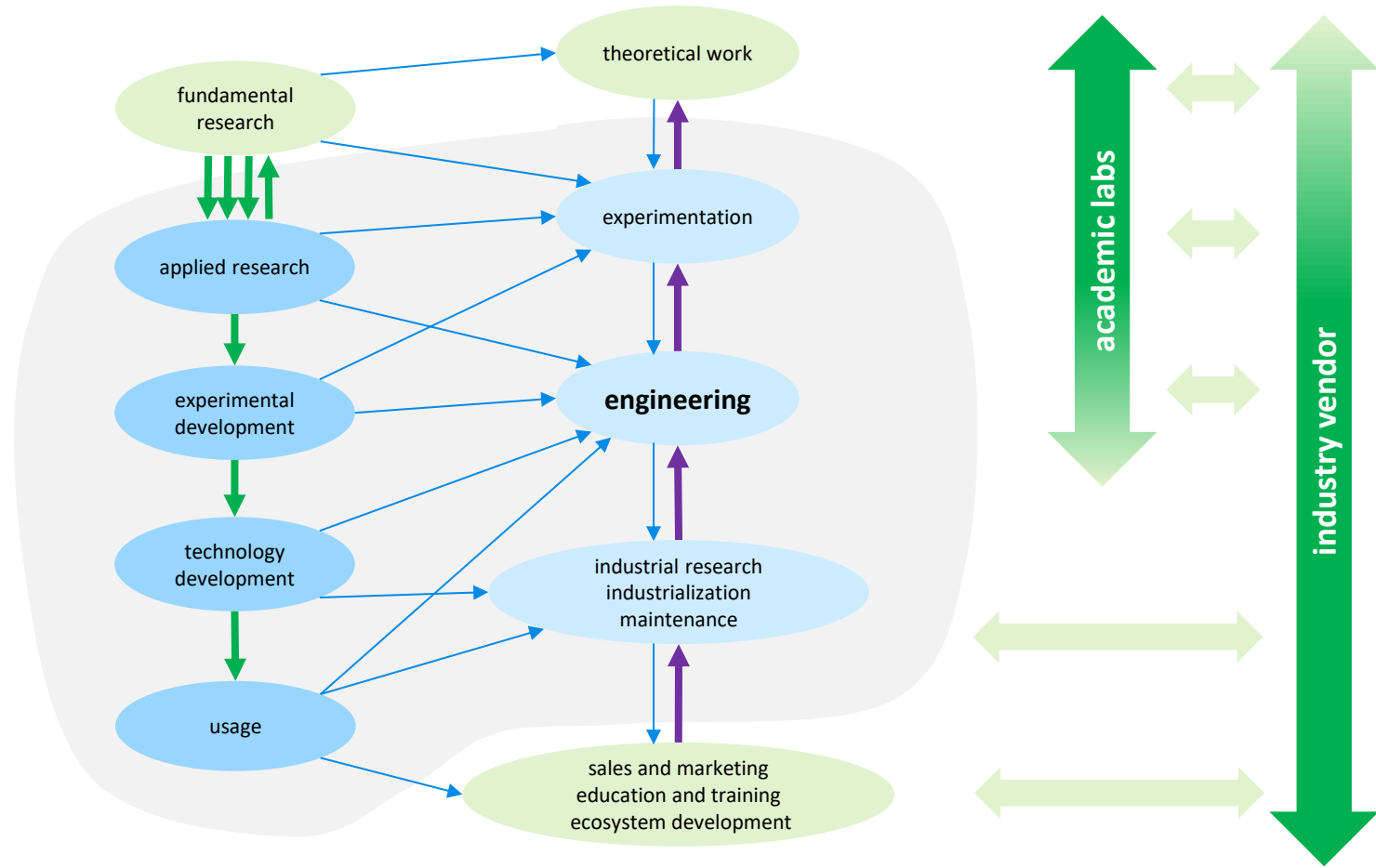
generic constraints

- talent
- funding
- competition
- evaluation
- patentability



specific constraints

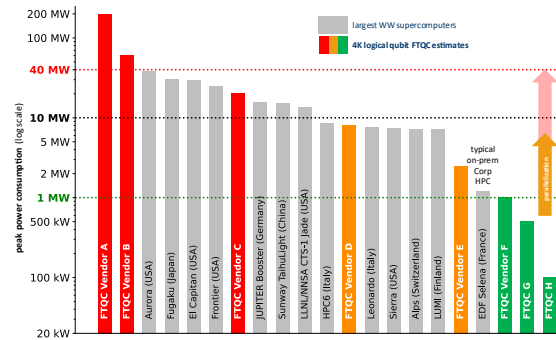
- find good questions
 - advance science
 - falsifiability
 - publish
-
- project milestones
 - enabling technologies
 - multi-skills integration
 - reproducibility
-
- user needs (UX, TCO, ROI)
 - roadmaps
 - investors pressure
 - market size
 - economies of scale
 - scaling manufacturing
 - business models



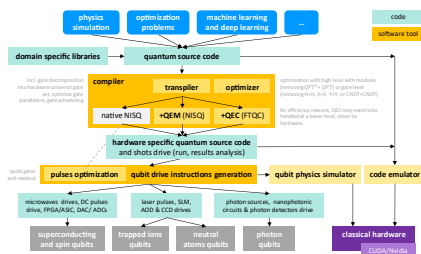
A 3D exploded view of the ITER tokamak components. The image shows the toroidal field coils (large red and white striped rings), the poloidal field coils (smaller red and white striped rings), and the central column structure (blue and white). The components are arranged in a circular pattern, illustrating the complex geometry of the tokamak.

The timeline illustrates the progression of quantum computing technology from 2015 to 2035. It is categorized into five main areas: Quantum & Superconducting, Hybrid, Analog, Digital, and Quantum. Key milestones include the first quantum advantage demonstration in 2019, the first quantum advantage demonstration in 2020, the first quantum advantage demonstration in 2021, the first quantum advantage demonstration in 2022, the first quantum advantage demonstration in 2023, the first quantum advantage demonstration in 2024, the first quantum advantage demonstration in 2025, the first quantum advantage demonstration in 2026, the first quantum advantage demonstration in 2027, the first quantum advantage demonstration in 2028, the first quantum advantage demonstration in 2029, the first quantum advantage demonstration in 2030, the first quantum advantage demonstration in 2031, the first quantum advantage demonstration in 2032, the first quantum advantage demonstration in 2033, the first quantum advantage demonstration in 2034, and the first quantum advantage demonstration in 2035.

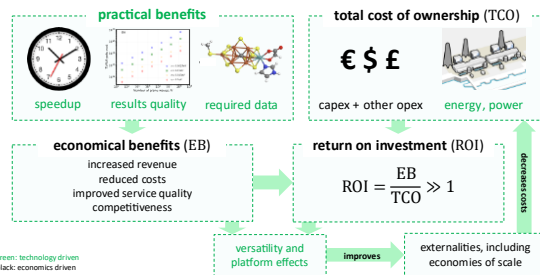
FTQC engineering



energetics engineering



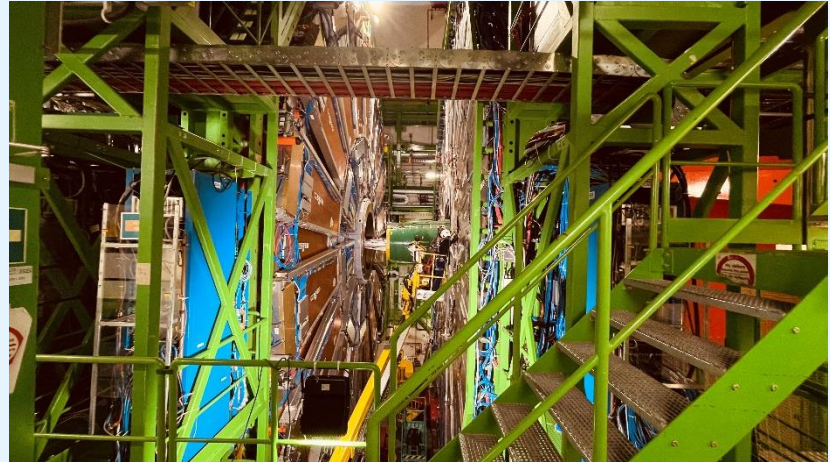
software engineering



economics and engineering

science and engineering at CERN LHC

how fundamental
research benefits from
engineering



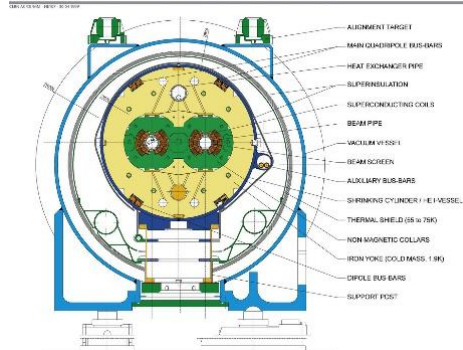
High Energy Physics - Experiment

[Submitted on 27 Mar 2025 (v1), last revised 6 Apr 2025 (this version, v2)]

Long-Baseline Atom Interferometry

Antun Balaz, Diego Blas, Oliver Buchmueller, Sergio Calatroni, Laurentiu-Ioan Caramete, David Cerdeno, Maria Luisa Chiofalo, Fabio Di Pumpo, Goran Djordjevic, John Ellis, Pierre Fayet, Chris Foot, Naeur Gaaloul, Susan Gardner, Barry M Garraway, Alexandre Gauguet, Enno Giese, Jason M. Hogan, Onur Hosten, Alex Kehagias, Eva Kilian, Tim Kovachy, Carlos Lacasta, Marek Lewicki, Elias Lopez Asamar, J Luis Lopez-Gonzalez, Nathan Lundblad, Michele Maggiore, Christopher McCabe, John McFerran, Gaetano Milet, Peter Millington, Gavin W. Morley, Senad Odzak, Chris Overstreet, Krzysztof Pawlowski, Emanuele Pelucchi, Johann Rafelski, Albert Roura, Marianna S. Safronova, Florian Schreck, Olga Sergijenko, Yeshpal Singh, Marcelle Soares-Santos, Nikolaos Stergioulas, Guglielmo M. Tino, J. N. Tinsley, Hendrik Ulbricht, Maurits van der Grinten, Ville Vaskonen, Wolf von Klitzing, Andre Xuereb, Emmanuel Zambirini Cruzeiro

LHC DIPOLE : STANDARD CROSS-SECTION



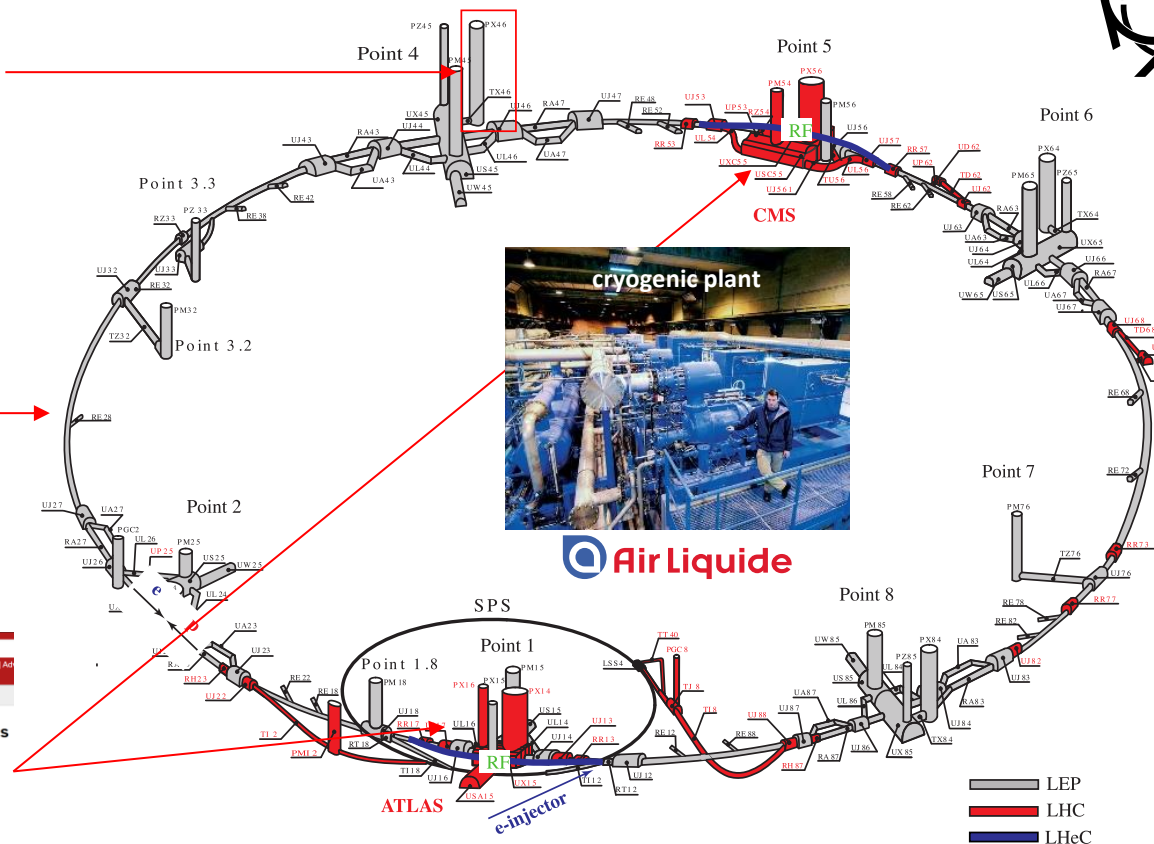
High Energy Physics - Experiment

[Submitted on 31 Jul 2012 (v1), last revised 31 Aug 2012 (this version, v2)]

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

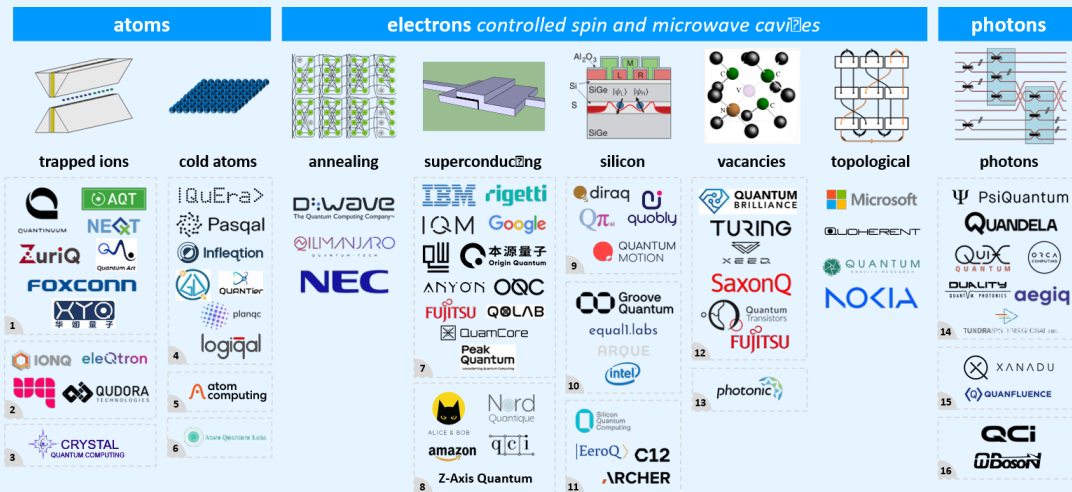
The ATLAS Collaboration

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$ in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ in 2012. Individual searches in the channels $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ in the 8 TeV data are combined with previously published results of searches for $H \rightarrow ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4 (\text{stat}) \pm 0.4 (\text{sys}) \text{ GeV}$ is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9} , is compatible with the production and decay of the Standard Model Higgs boson.



FTQC engineering

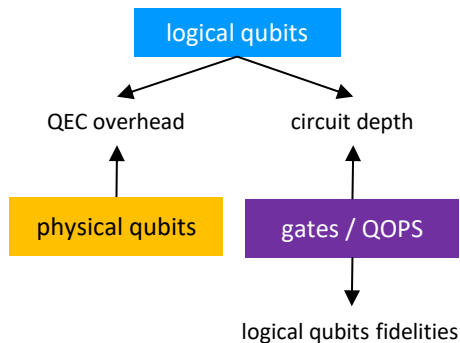
full-stack components
integration to deliver on
the promises of FTQC



what should we have in FTQC roadmaps?

basic features

- # logical qubits.
- supported circuit size / logical error rates.
- # physical qubits.



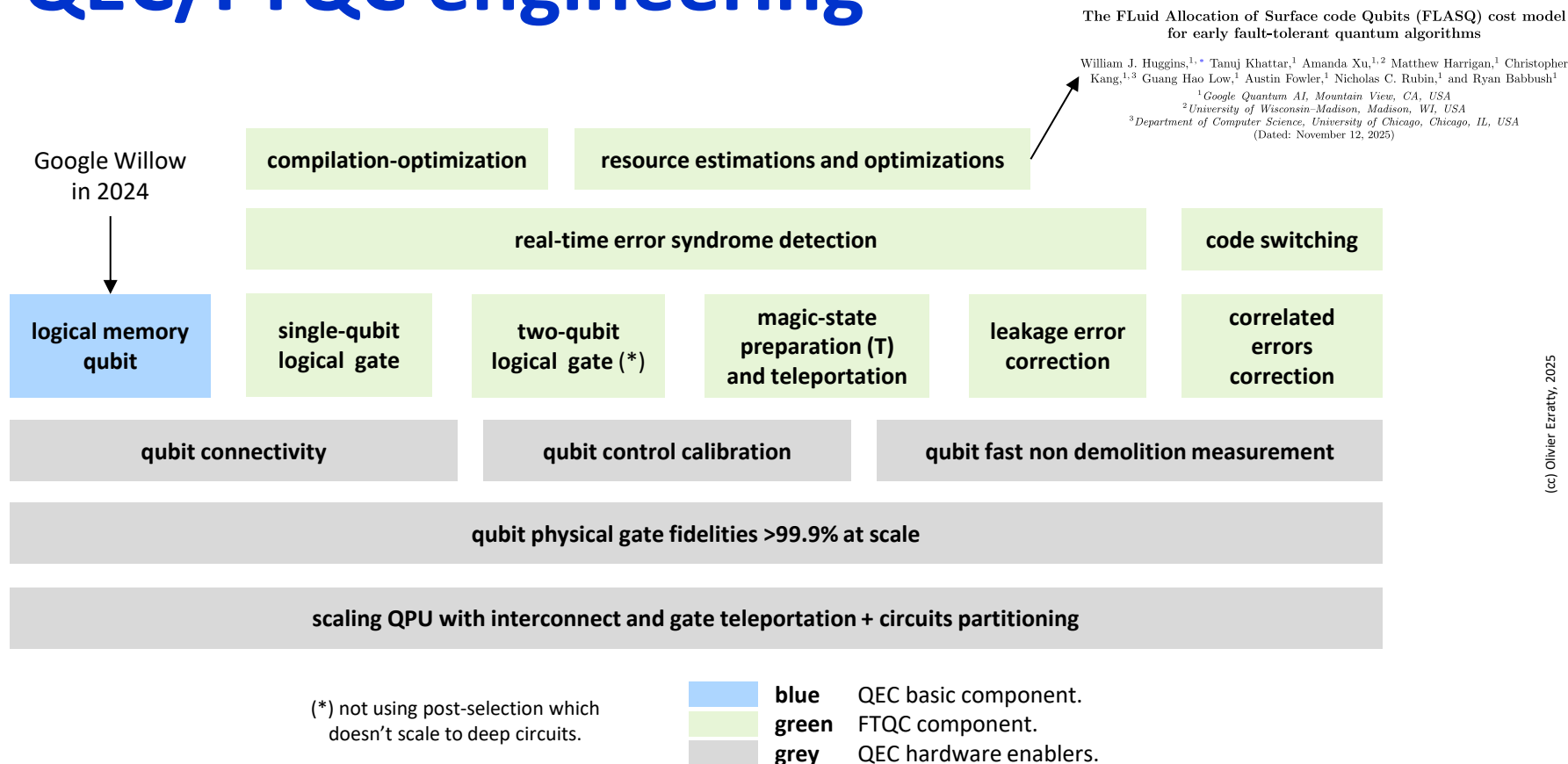
engineering “features”

- supported range of applications.
- clock speed and QLOPs/s.
- planned QEC codes and methods.
- processor size & reliance on QPU interconnect.

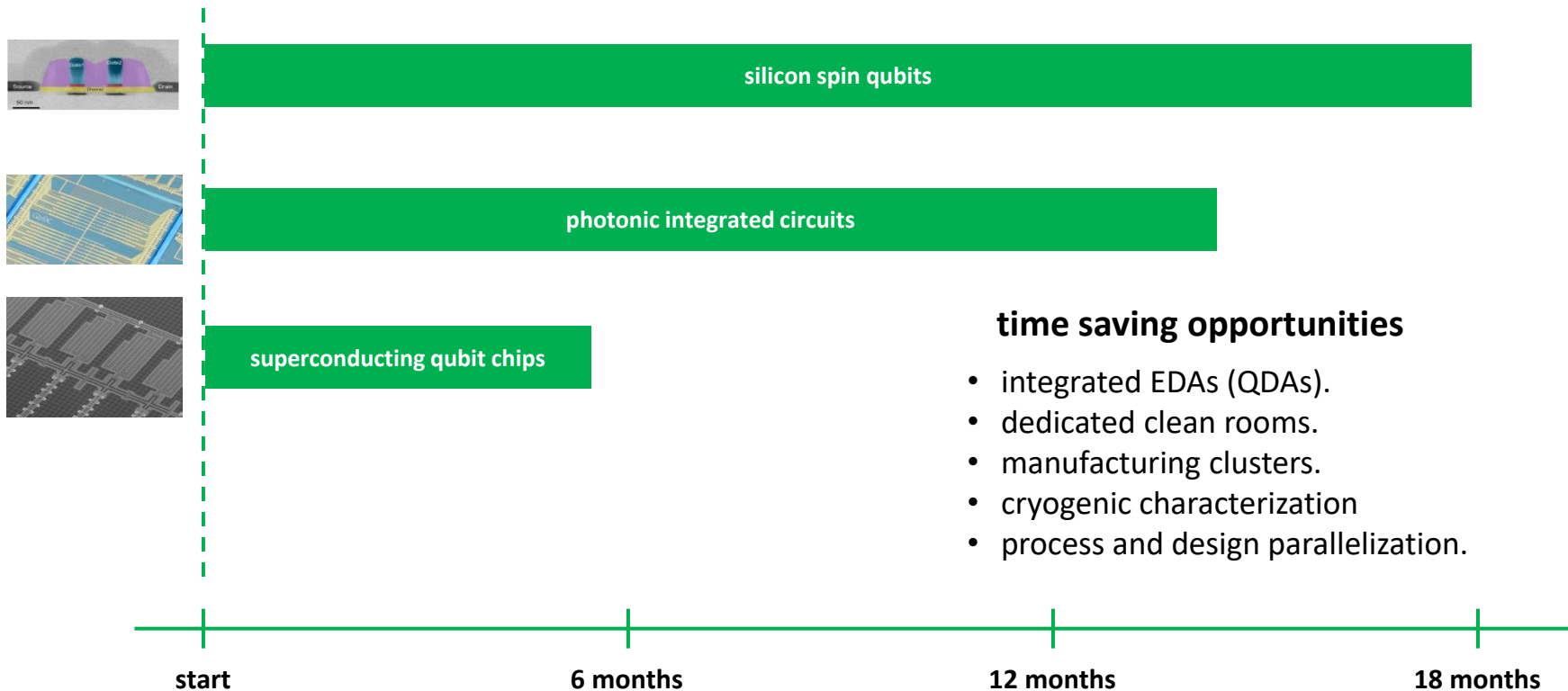
- peak power consumption in W.
- components operating temperature.
- QPU weight and size.
- temperature variability.
- components MTBF.
- capex/opex cost structure.

operational metrics

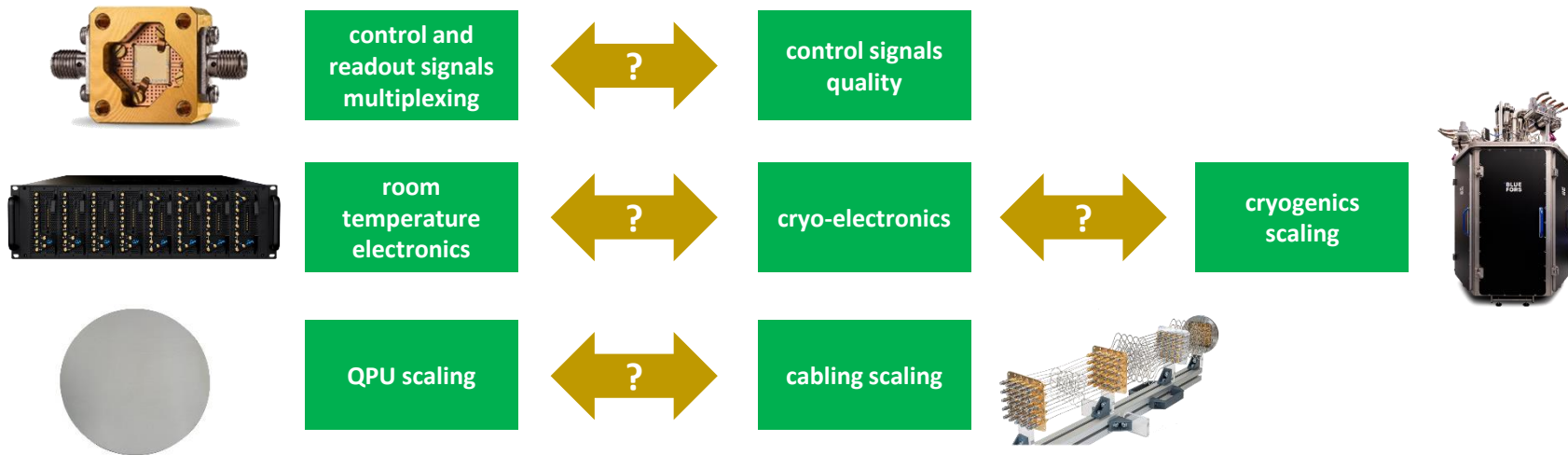
QEC/FTQC engineering



chips “design to test” iteration cycles



enabling tech engineering trade-offs

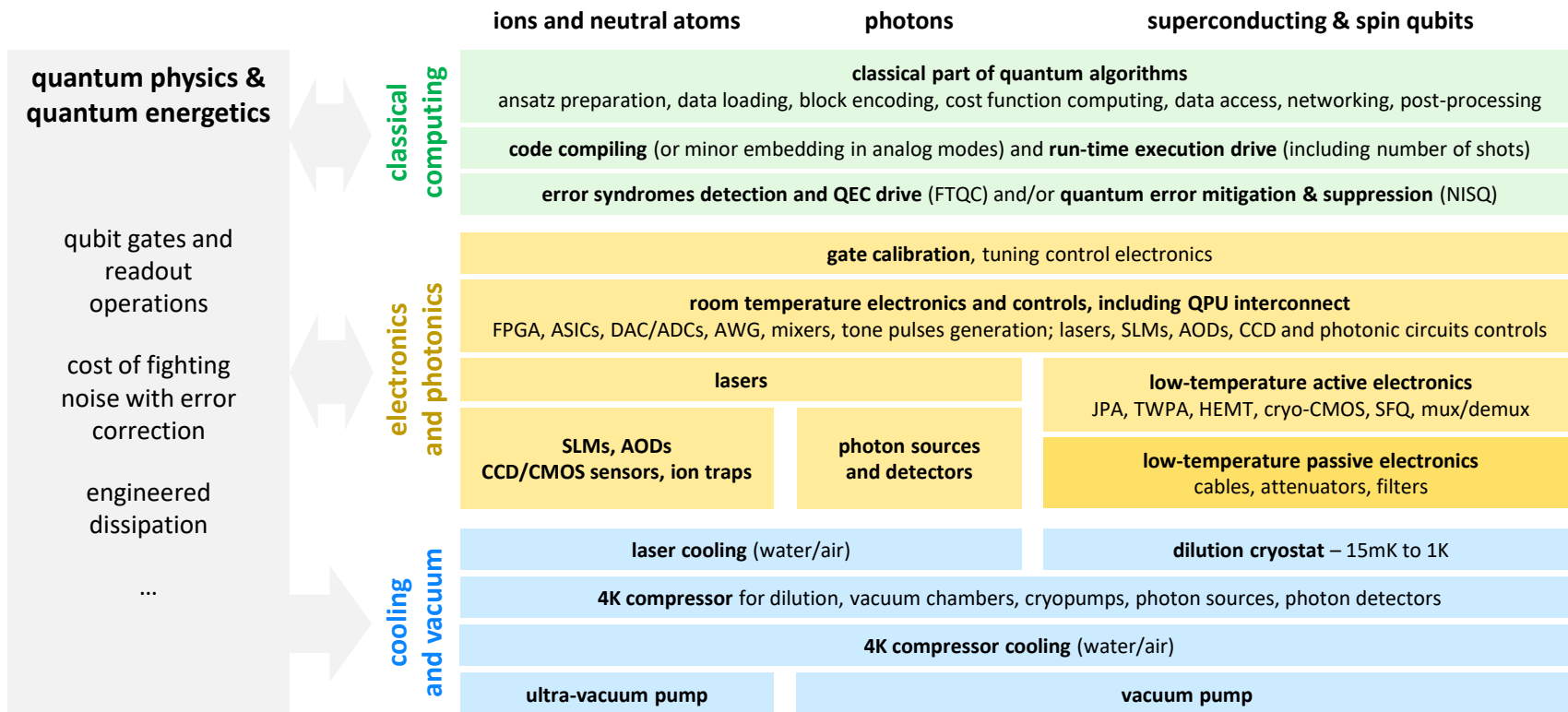


quantum computing energetics engineering

system architecture using reductionist
and holistic optimizations under multiple
constraints



full-stack energetic costs decomposition

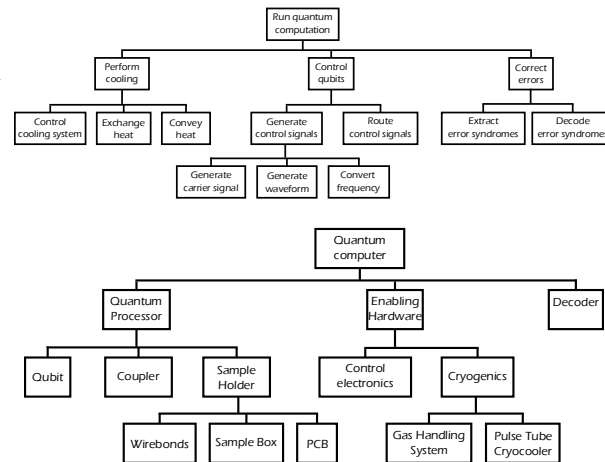


energetic systems architecture approach

1. functional and product breakdowns
2. estimate baseline resources
3. optimize energy efficiency under constraints
4. mix reductionist and holistic approaches
5. handle operational trade-offs
6. measure and benchmark
7. integrate an economical view

detailed in
next slide

FTQC energetics paper
(in preparation).



credit: Jeremy Stevens, Alice&Bob

The energetic challenges of fault-tolerant quantum computing

Marco Fellous-Asiani,¹ Pierre-Emmanuel Emeriau,² Jeremy Stevens,³
Marco Pezzutto,^{4,5,6} Yasser Omar,^{4,5,6} and Olivier Ezratty^{7,8,*}

¹Inria

²Quandela

³Alice&Bob

⁴Instituto Superior Técnico, Universidade de Lisboa, Portugal

⁵PQI – Portuguese Quantum Institute, Portugal

⁶Physics of Information and Quantum Technologies Group,
Centro de Física e Engenharia de Materiais Avançados (CeFEMA), Portugal

⁷EPITA Research Lab

⁸Quantum Energy Initiative

from baseline estimates to optimizations

what

baseline resources

- ◆ use state of the art existing technologies.
- ◆ adding individual components resources.
- ◆ evaluate or measure idle, average and peak power.



$$[] + [] + [] + [] + [] = 100$$

reductionist optimizations

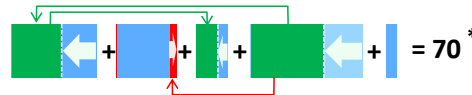
- ◆ account for future enabling technology developments.
- ◆ component level optimization.
- ◆ doesn't affect other components performance.
- ◆ doesn't add more noise.



$$[] + [] + [] + [] = 90^*$$

holistic optimizations

- ◆ interdependent optimizations.
- ◆ side effects on noise and task success metrics.
- ◆ various energy vs computing time or space-time trade-offs.



$$[] + [] + [] + [] = 70^*$$

examples

- ◆ all active components.
- ◆ classical computing (circuit preparation, compiler, error correction, post-processing, ...).

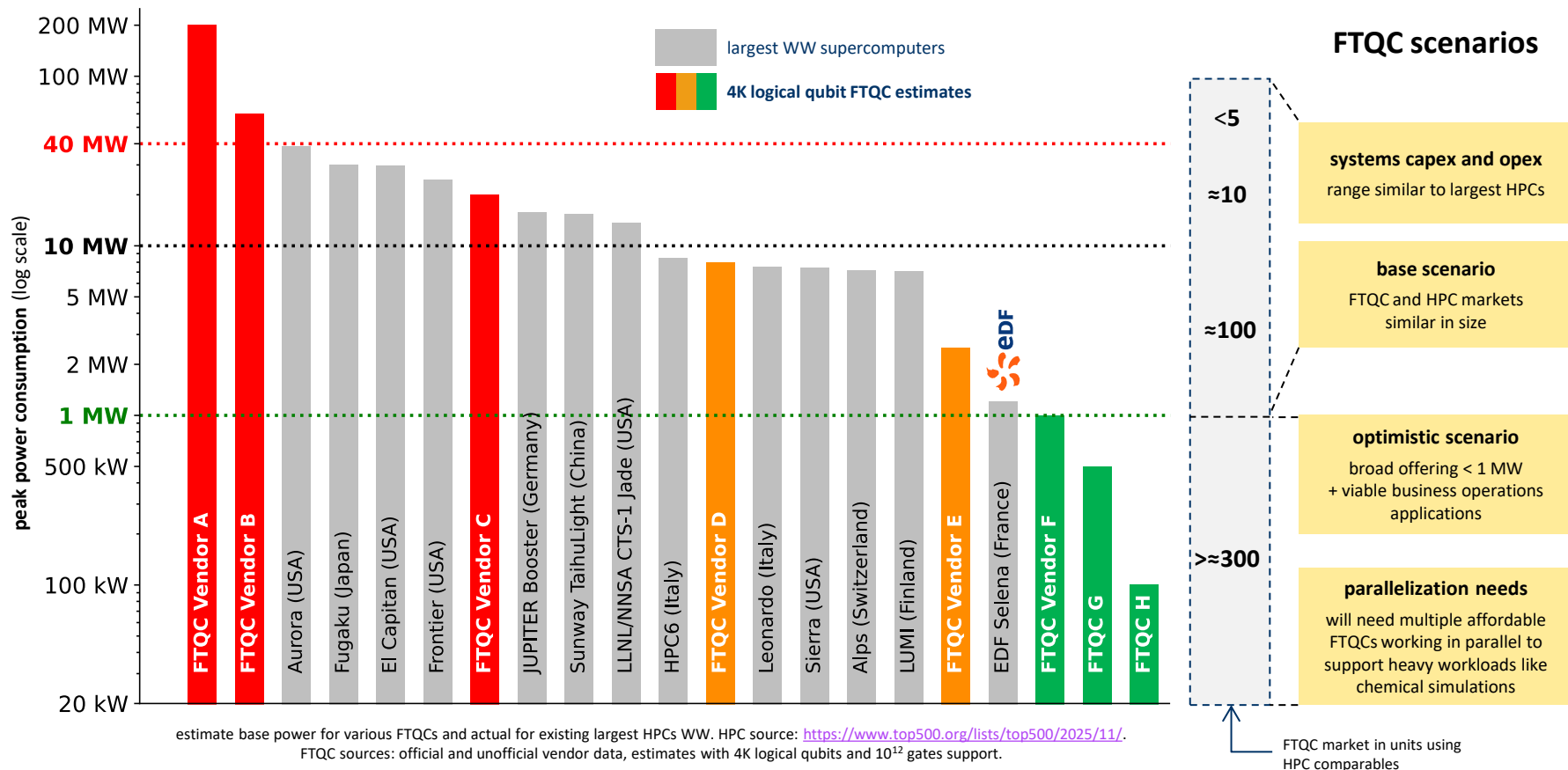
- ◆ cryogenics.
- ◆ control electronics.
- ◆ cable dissipation.
- ◆ compiler efficiency.

- ◆ moving electronics at cryogenic temperatures.
- ◆ using SFQ control electronics.
- ◆ changing qubit temperature.

system generic (power) or task dependent with a success metric (energy)

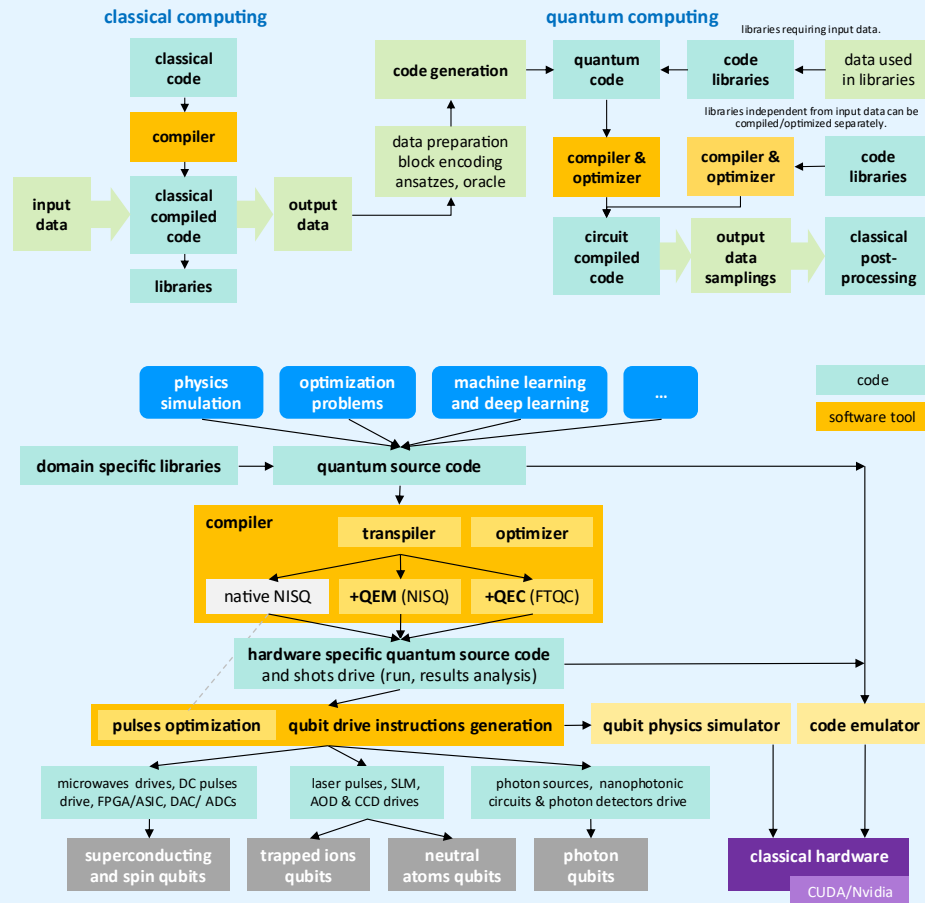
* % of baseline power or energy, for the sake of demonstration

FTQC vs HPC power baseline estimates

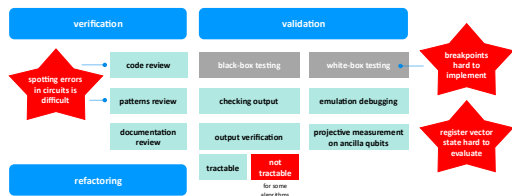
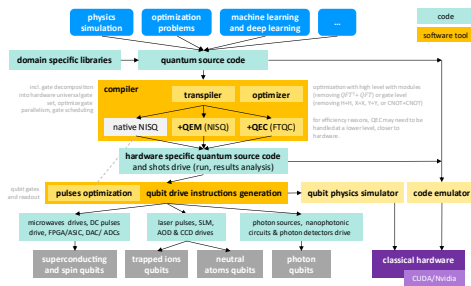
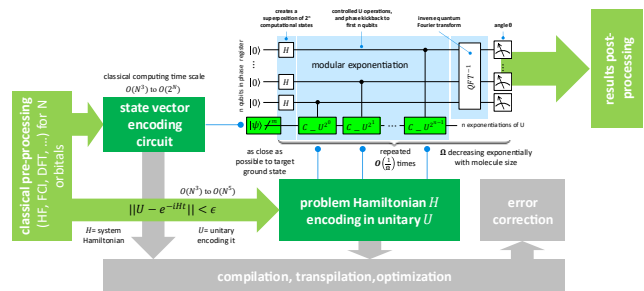


quantum software engineering

from quantum circuits to full-stack software engineering



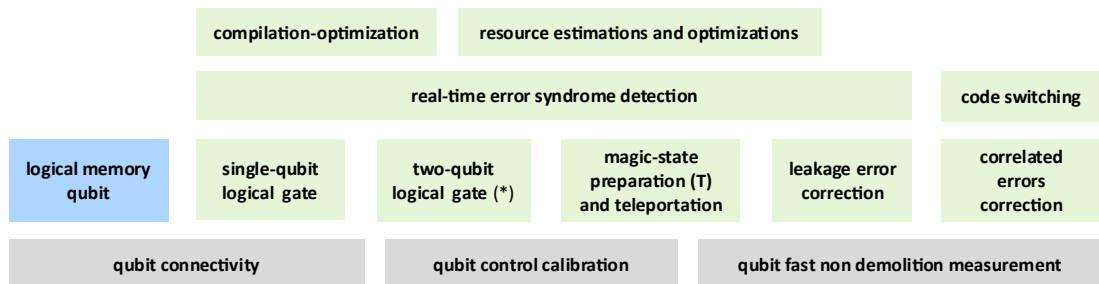
quantum software engineering



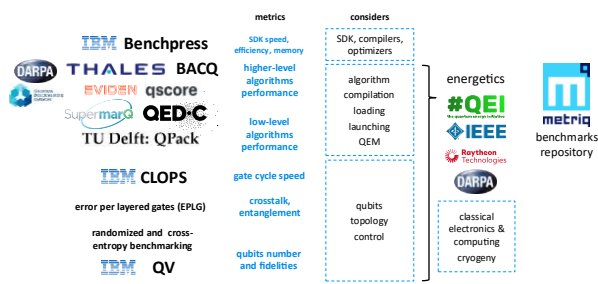
full-stack quantum solutions design

compilation chain

verification and validation



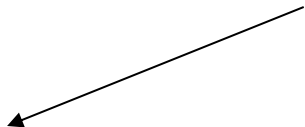
error correction and fault tolerance



benchmarking

theory vs engineering

aspect	science	engineering
obtaining some quantum computing speedups	- complexity class theory. - theoretical speedup.	- accounting for prefactors. - resource estimates. - using real-life user data sets. - compare with best-in-class classical solutions.



« On overexcitable children

Xavier Waintal responds (tl;dr Grover is still quadratically faster) »

Of course Grover's algorithm offers a quantum advantage!

Unrelated Update: Huge congratulations to Ethernet inventor Bob Metcalfe, for winning UT Austin's third Turing Award after Dijkstra and Emerson!

PHYSICAL REVIEW X **14**, 041029 (2024)

Opening the Black Box inside Grover's Algorithm

E. M. Stoudenmire¹ and Xavier Waintal²

¹Center for Computational Quantum Physics, Flatiron Institute,
162 5th Avenue, New York, NY 10010, USA

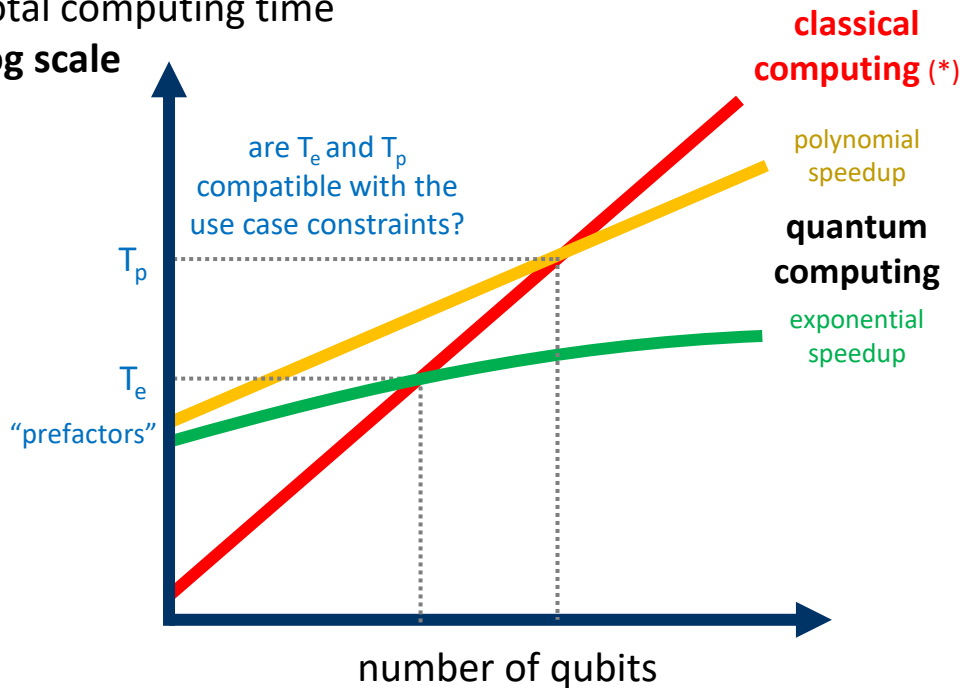
²Université Grenoble Alpes, CEA, Grenoble INP, IRIG, Pheliqs, F-38000 Grenoble, France



(Received 30 May 2023; revised 9 July 2024; accepted 5 August 2024; published 1 November 2024)

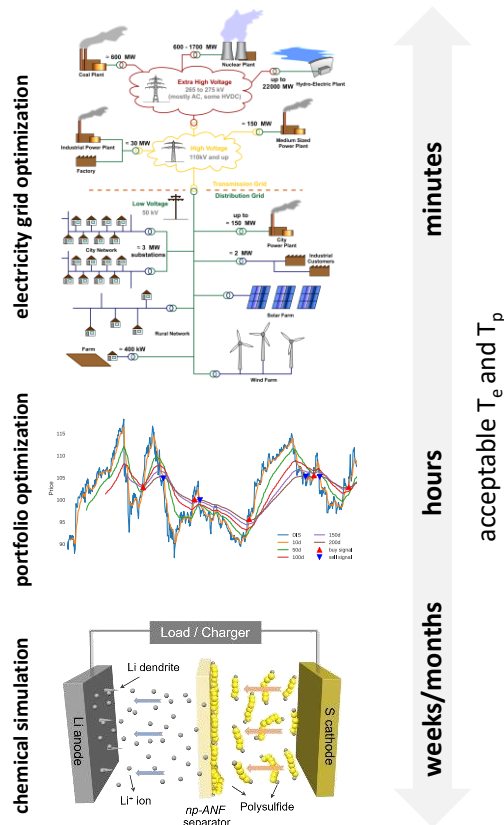
theoretical vs practical speedups

total computing time
log scale



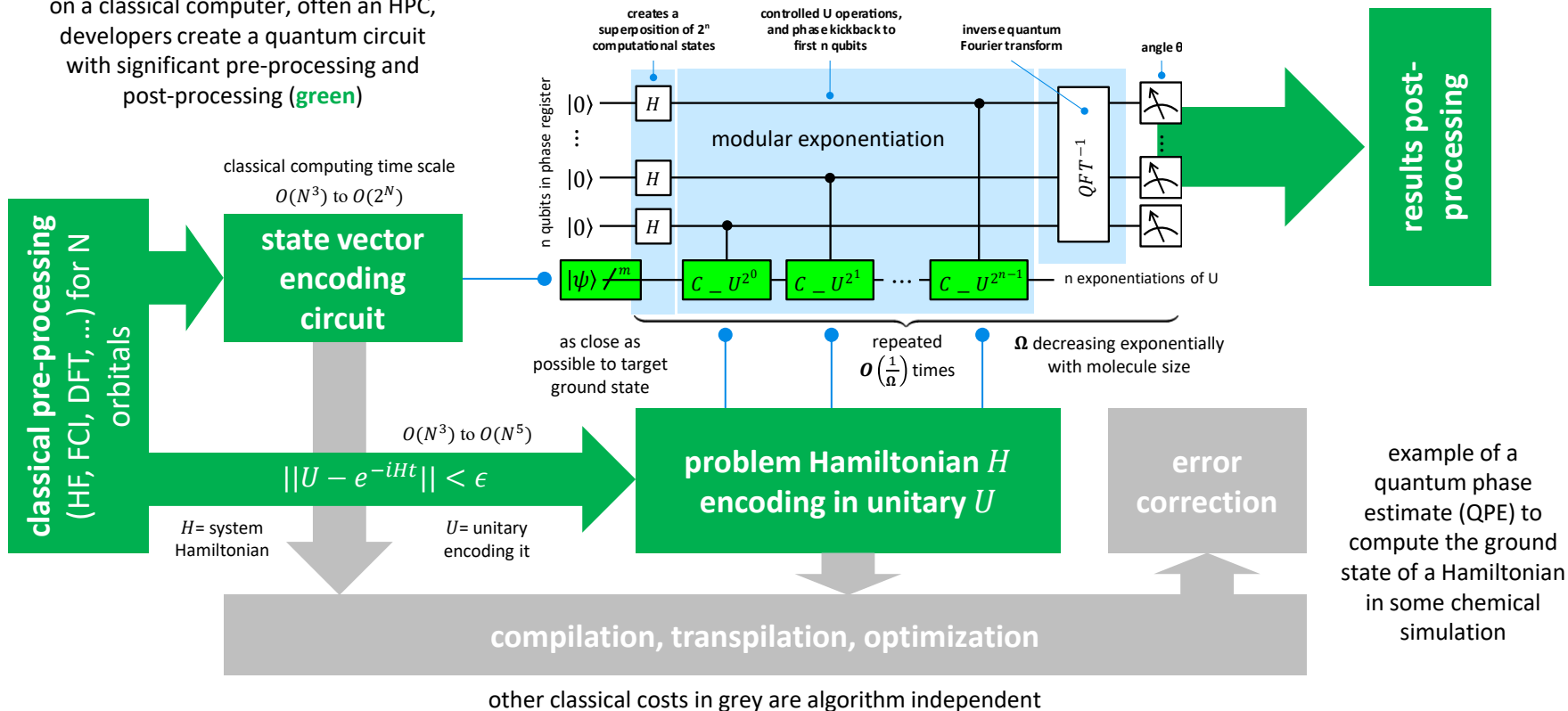
inspired by [Opening the Black Box inside Grover's Algorithm](#)
by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

(*) for a fair comparison, the classical computer can be as expensive and/or energy hungry as the QPU.



quantum algorithm full-stack engineering

on a classical computer, often an HPC, developers create a quantum circuit with significant pre-processing and post-processing (green)



HPC QPU integration

- when is colocation mandated?
- what bandwidth is required?
- what HPC size next to QPUs?
- data center constraints?

Integration of Quantum Accelerators into HPC: Toward a Unified Quantum Platform

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<https://arxiv.org/abs/2407.18527>

Dependable Classical-Quantum Computer Systems Engineering

Edoardo Giusto*, Santiago Nuñez-Corrales†, Phuong Cao‡, Alessandro Cilardo*, Ravishankar K. Iyer‡, Weiwen Jiang||, Paolo Rech§, Flavio Vella§, Bartolomeo Montrucchio¶, Samudra Dasgupta**, and Travis S. Humble **

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†National Center for Supercomputing Applications, Urbana, IL, US

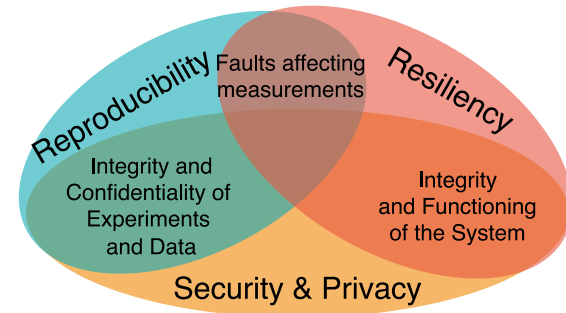
‡University of Illinois Urbana-Champaign, US

§University of Trento, Italy

¶Politecnico di Torino, Italy

|| George Mason University, VA, US

** Oak Ridge National Laboratory, TN, US



<https://arxiv.org/abs/2408.10484>

quantum software engineering tools

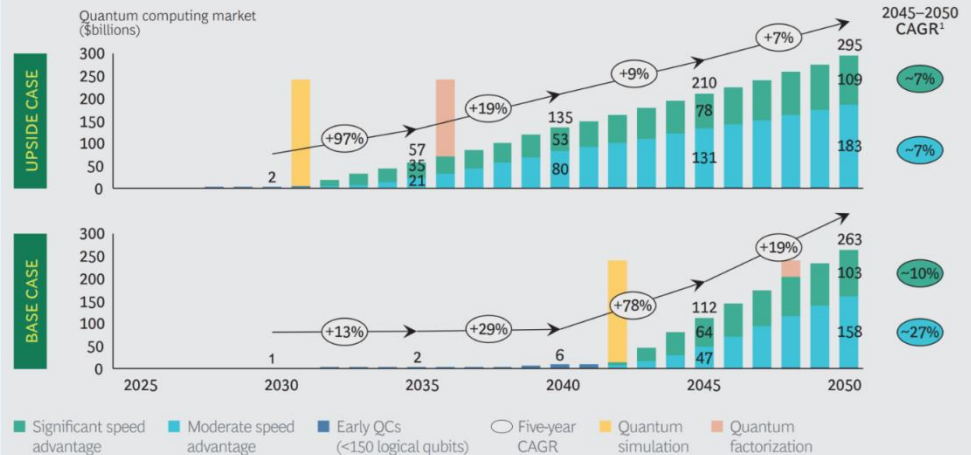
	academic experiments	industry applications tools
software tools	• pulse-level control (NISQ). • prototype SDKs. • Python notebooks. • custom emulators. • hardware-level qubit simulators. • tomography software tools. • research-oriented transpilers. • experiment data analysis tools. • data-analysis machine learning tools. • post-selection-based error correction.	• full-stack QEC and FTQC. • stable APIs and gate set • production-grade SDKs. • resource estimators. • quantum circuits partitioning tools. • hardened compilers and optimizers. • debugging, verification and certification. • telemetry and performance monitoring. • cloud/HPC operations. • job queuing and scheduling. • QPU time billing. • operational research tools.

quantum engineering and economics

TCO-ROI and externalities

EXHIBIT 3 | The Speed of Market Growth Depends on Technical Milestones

UPSIDE CASE (10:1 RATIO IN ERROR CORRECTION): MAJOR APPLICATIONS BY 2031
BASE CASE (500:1): MAJOR APPLICATIONS BY 2042



Source: BCG analysis.

Note: Assumes machine learning grows at current projected rate of ~18% CAGR until 2037 and then levels off at 2% CAGR per year until reaching a steady-state growth rate of ~7% applied to majority of other applications. Because of rounding, numbers may not add up to the totals shown.

¹CAGR based on 2045–2050 to compensate for downward bias of higher initial adoption rates of solutions that offer significant and moderate speed advantages.

Moore's law *duality*

technology

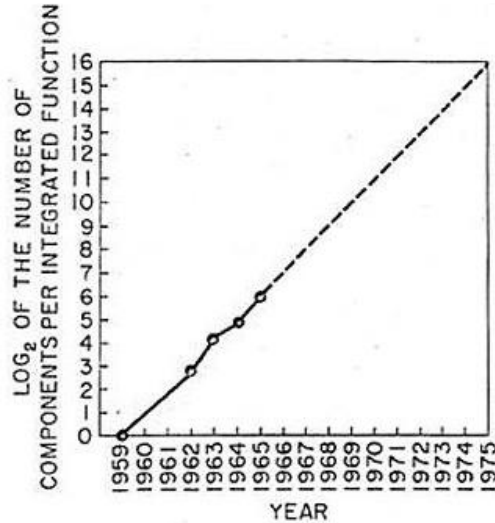


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

“complexity”
= # of transistors on a chip

The experts look ahead

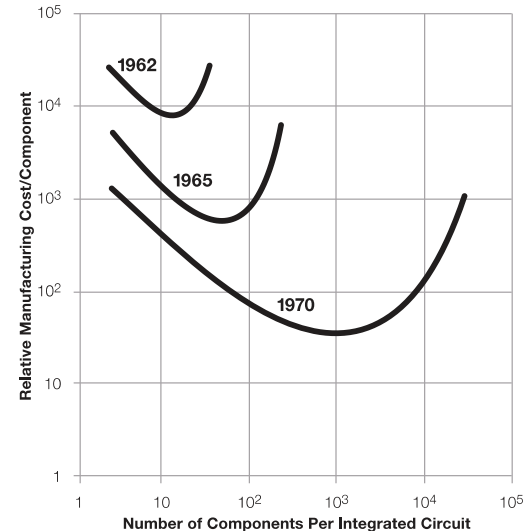
Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

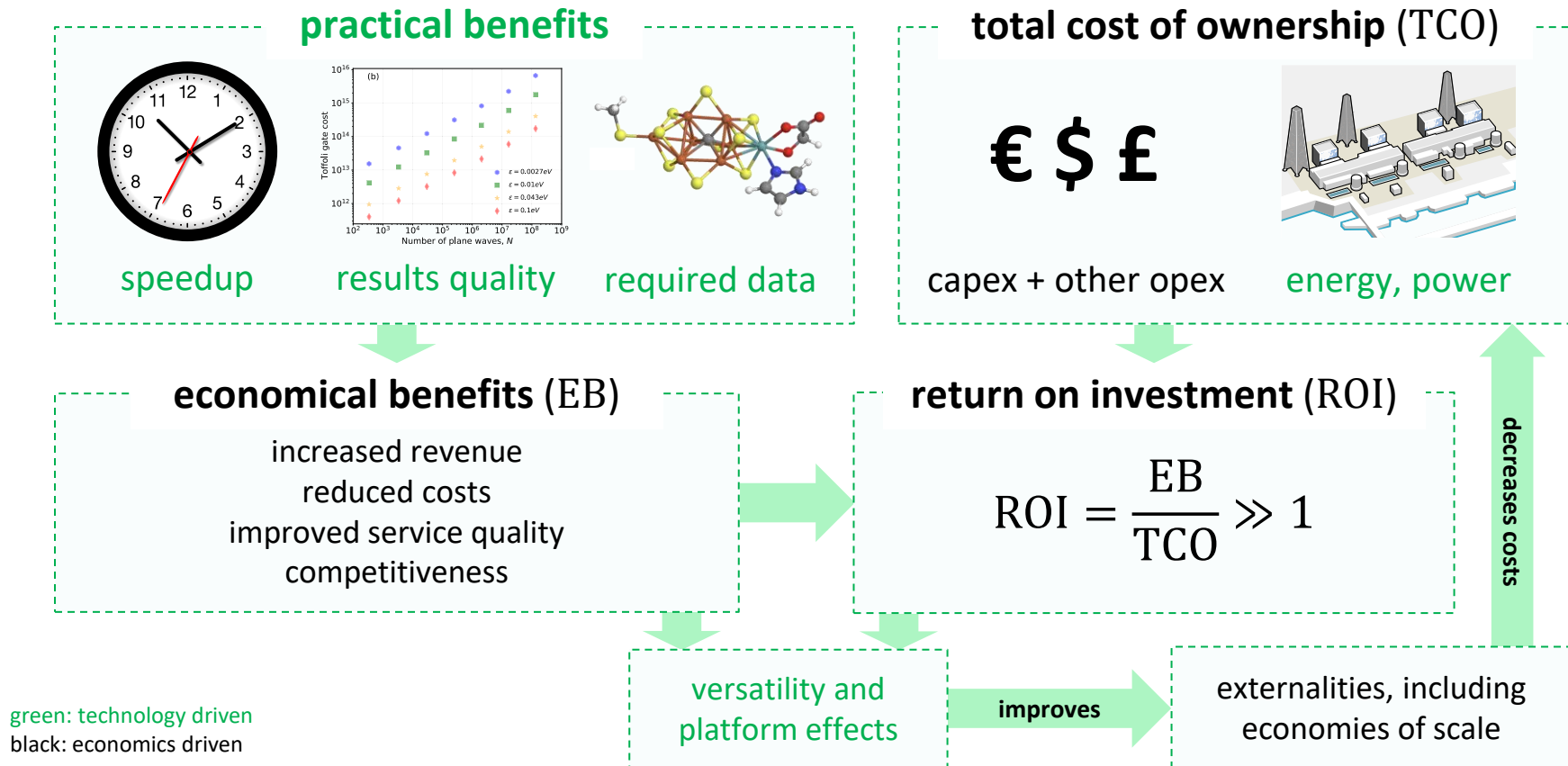
Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

economics



**also, an economic
driven law**

from value to return on investment



discussion



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now