

Quantum Computing

A Practical Perspective

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Politecnico di Milano



Agenda

- November 7th → Theory Recap on Quantum Computing
- November 20th → Initial Setup and First Experiments
- November 21st → Grover's Algorithm
- November 25th → Combinatorial Optimization
- November 28th → VQE, QNN, QMC
- December 3rd → Quantum Error Correction & Mitigation – Projects Presentation

(it may be subject to variations)

Initial Setup: Steps To Do

- Get a MathWorks MATLAB license from polimi
- Install MATLAB R2024b on your local machine
- Install MATLAB Support Package for Quantum Computing
- Sign up to IBM Quantum

Get a license

The screenshot shows the Mathworks Matlab website at the URL <https://www.software.polimi.it/mathworks-matlab/?lang=en#toggle-id-2>. The page features a navigation bar with 'ICT SERVICES SOFTWARE' and a sidebar with filters like 'Teachings adopting this software', 'Availability in classroom', and 'Accessible on Virtual Desktop'. The main content area is titled 'Mathworks Matlab' and includes a description of the software, system requirements (Windows, Linux, macOS), and a section titled 'How to get the software' with sub-sections for 'Teaching staff', 'Students', and 'PhD students'. A blue callout box with the text 'Go to this link' points to the URL in the browser's address bar. Another blue callout box with the text 'Create a MathWorks Account' points to the '1. Create a Mathworks account' step in the 'Download' section. A cookie consent banner is visible at the bottom of the page.

Mathworks Matlab

Go to this link

How to get the software

Licenses, recipients, request and download methods

Teaching staff

Students

- Annual license
- Edition: Total Academic Headcount Licenses – Student Option (basic package, subscribed optional modules and upgrades)
- The software can be installed on personal PCs for up to four installations.

Download

1. Create a Mathworks account
2. Download the software

PhD students

Technical and administrative staff

This site uses cookies. By continuing to browse the site, you are agreeing to our use of cookies. [Agree](#) [Disagree](#) [Settings](#)

Create a MathWorks Account

Get a license

MathWorks®

Politecnico di Milano

Accesso MATLAB per Politecnico di Milano

MATLAB e Simulink:

- utilizzato da oltre 100.000 aziende, dai leader del mercato alle startup
- Citati in oltre 4 milioni di pubblicazioni scientifiche

Esplora esempi reali dei risultati tecnici ottenuti dagli utenti di MATLAB e Simulink.

Ottieni MATLAB e Simulink

Entrambi sono disponibili tramite la licenza del tuo Ateneo.

[Visualizza l'elenco dei prodotti disponibili](#)

Accedi per iniziare

Impara le nozioni base, sviluppa le competenze

Trova il formato più adatto a te. Le risorse didattiche gratuite di MATLAB e Simulink includono corsi online interattivi, documentazione, esempi di codice e video sulle funzionalità dei prodotti.

[Vedi i corsi autogestiti](#) | [Ricerca di documentazione, esempi e video](#)

Click here to login

Get a license

- Use your @mail.polimi.it e-mail as a MathWorks account
- Follow all the steps and fill in the required data
- At the end of the process, your account should be correctly enabled with a valid license

Install MATLAB R2024b

The screenshot shows the MathWorks download page for MATLAB R2024b. The browser address bar shows the URL `mathworks.com/downloads/?status=SUCCESS`. The page has a blue header with the MathWorks logo and navigation links. Below the header, there are two blue callout boxes with arrows pointing to specific elements on the page. The first box, labeled "Go to this link", points to the URL in the address bar. The second box, labeled "Download a compatible MATLAB version", points to the "Download for Windows" button. The page content includes a "Select Release" dropdown menu set to "R2024b", a "I Want To:" dropdown menu set to "Install Products", and a "Get MATLAB and Simulink Products" section. The footer contains links for Trust Center, Trademarks, Privacy Policy, Preventing Piracy, Application Status, and Contact Us, along with copyright information and a "United States" location selector.

mathworks.com/downloads/?status=SUCCESS

Downloads

FAQ | Installation and Licensing Help

R2024b

Select Release
R2024b

I Want To:
Install Products

Latest Features
Release Notes
System Requirements

Get MATLAB and Simulink Products

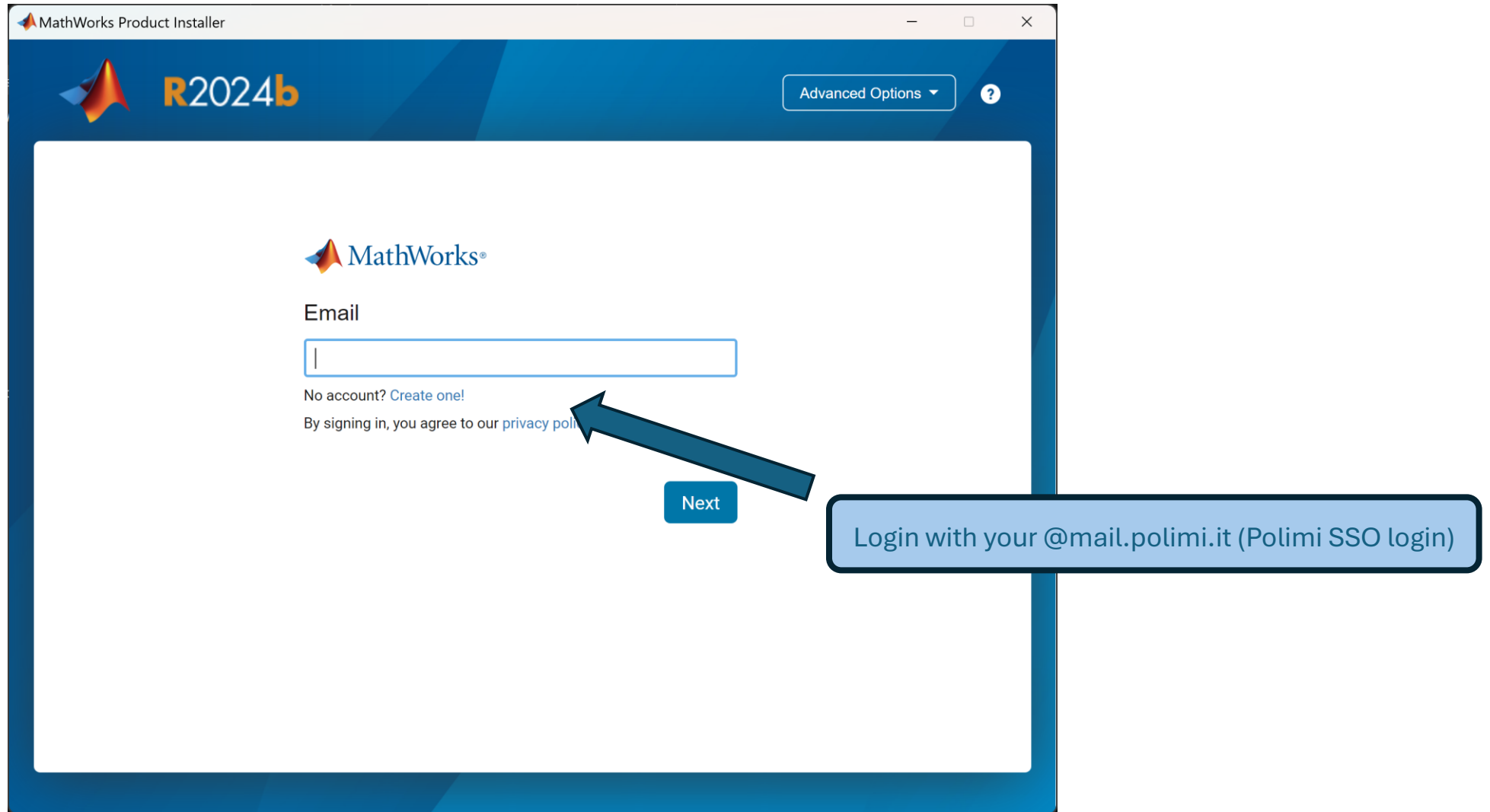
Download for Windows

[R2024b Update 2 \(14 Nov 2024\)](#)

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United States

Install MATLAB R2024b



MathWorks Product Installer

MathWorks®

R2024b

Advanced Options ?

Email

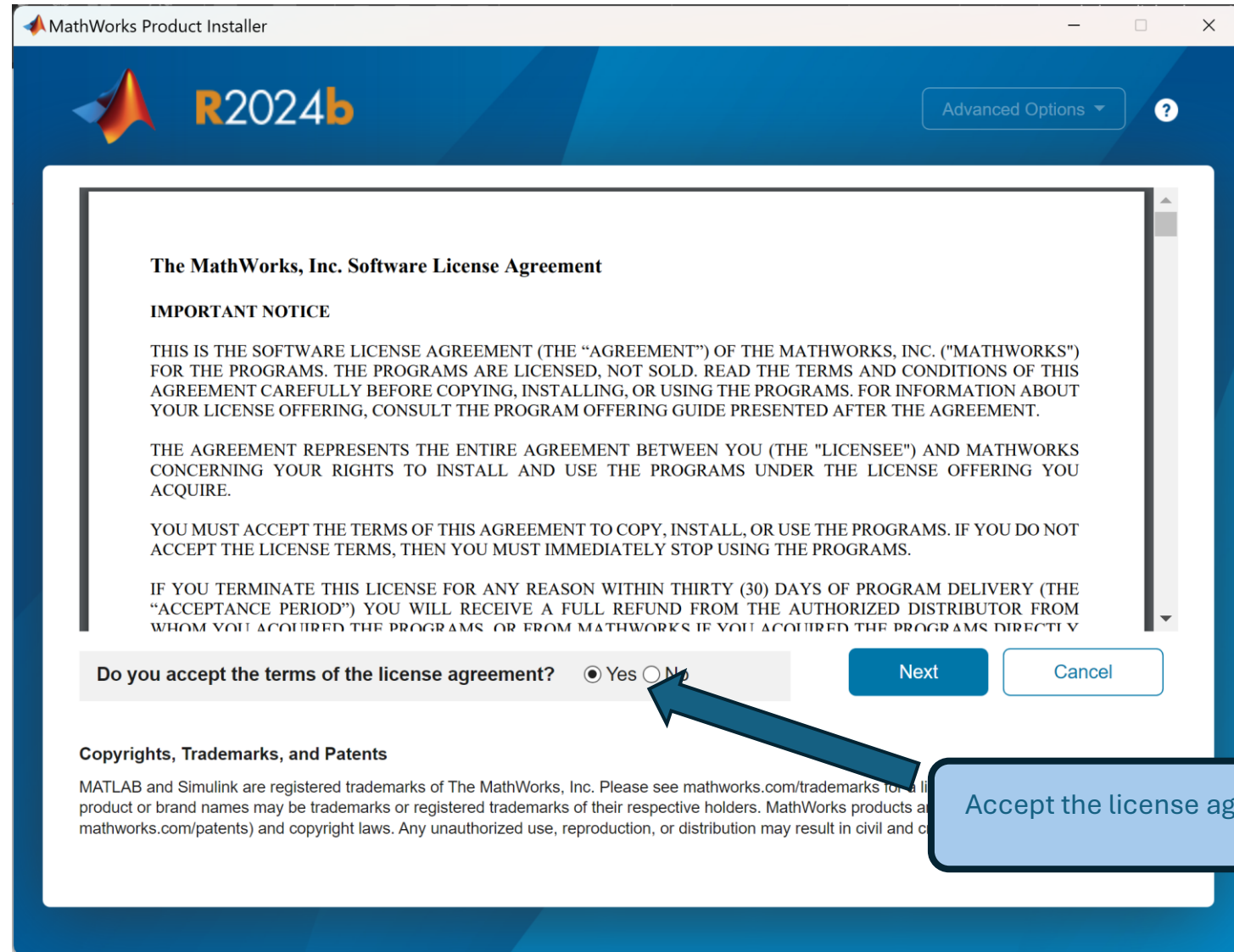
No account? [Create one!](#)

By signing in, you agree to our [privacy policy](#)

Next

Login with your @mail.polimi.it (Polimi SSO login)

Install MATLAB R2024b



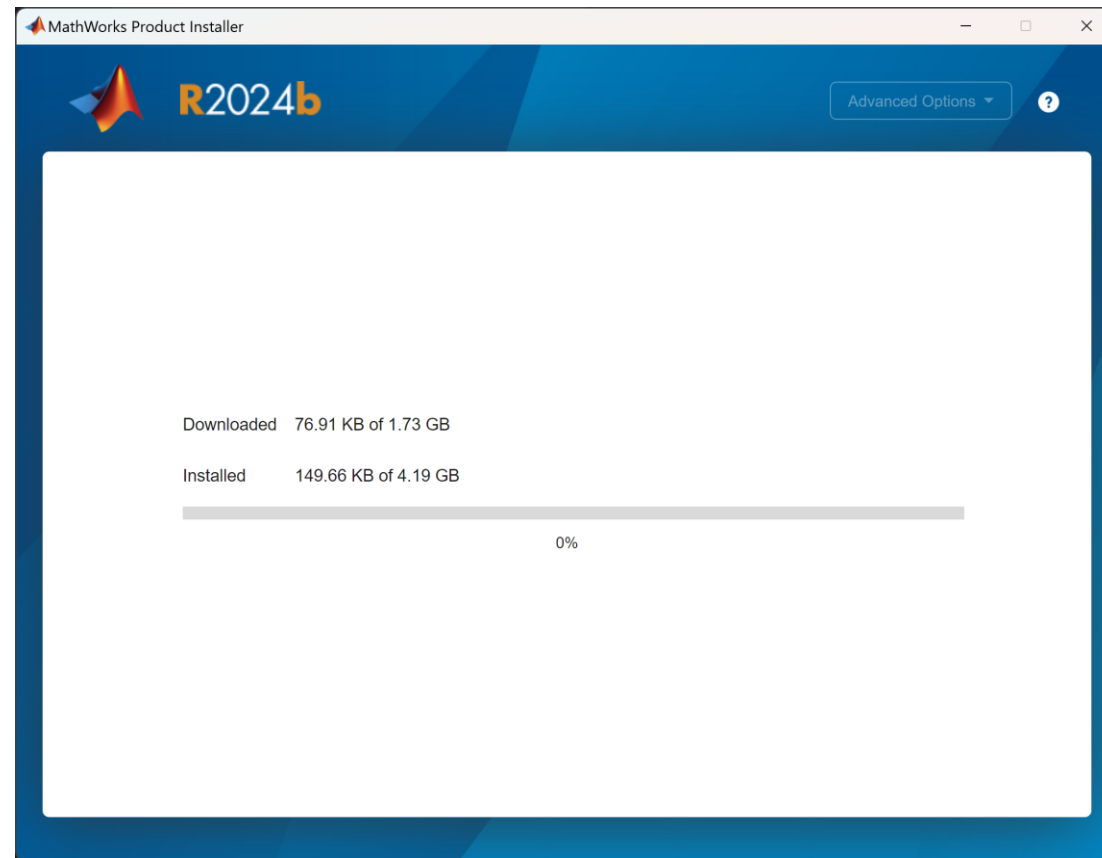
Accept the license agreement (after carefully reading it)

Install MATLAB R2024b

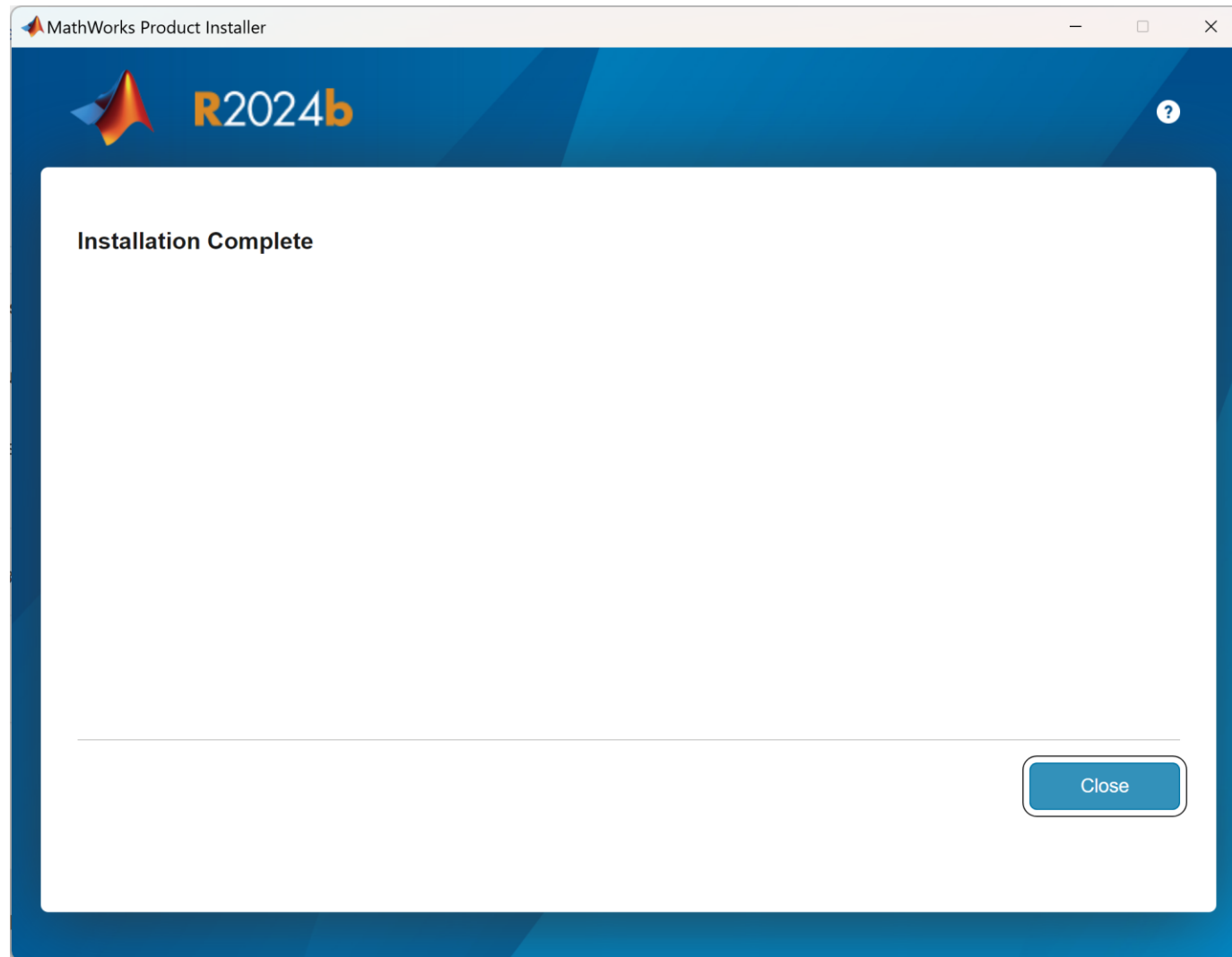
- Press “Next” a bunch of times and then “Begin Install”

Install MATLAB R2024b

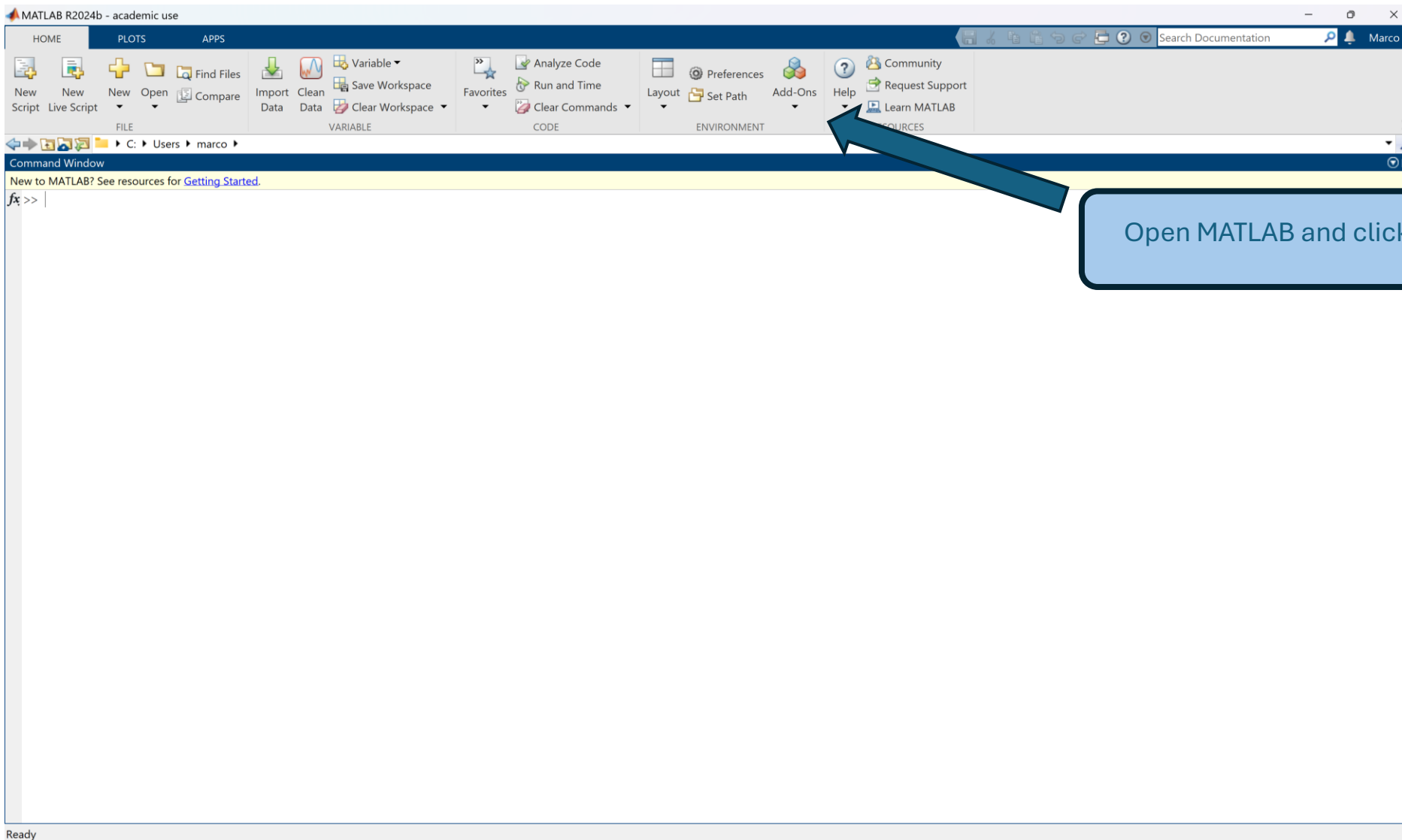
- Press “Next” a bunch of times and then “Begin Install”



Install MATLAB R2024b

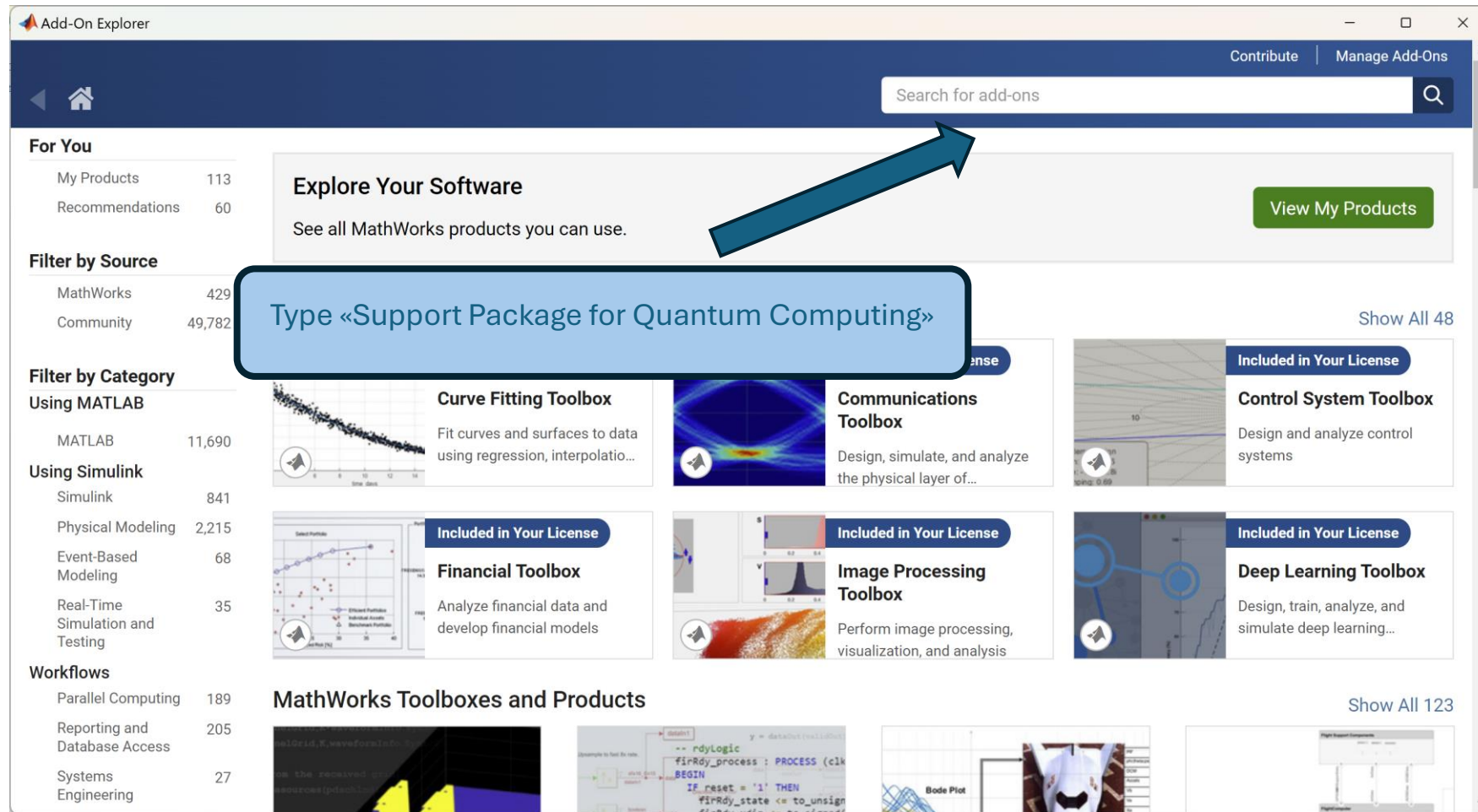


Install MATLAB Support Package for QC

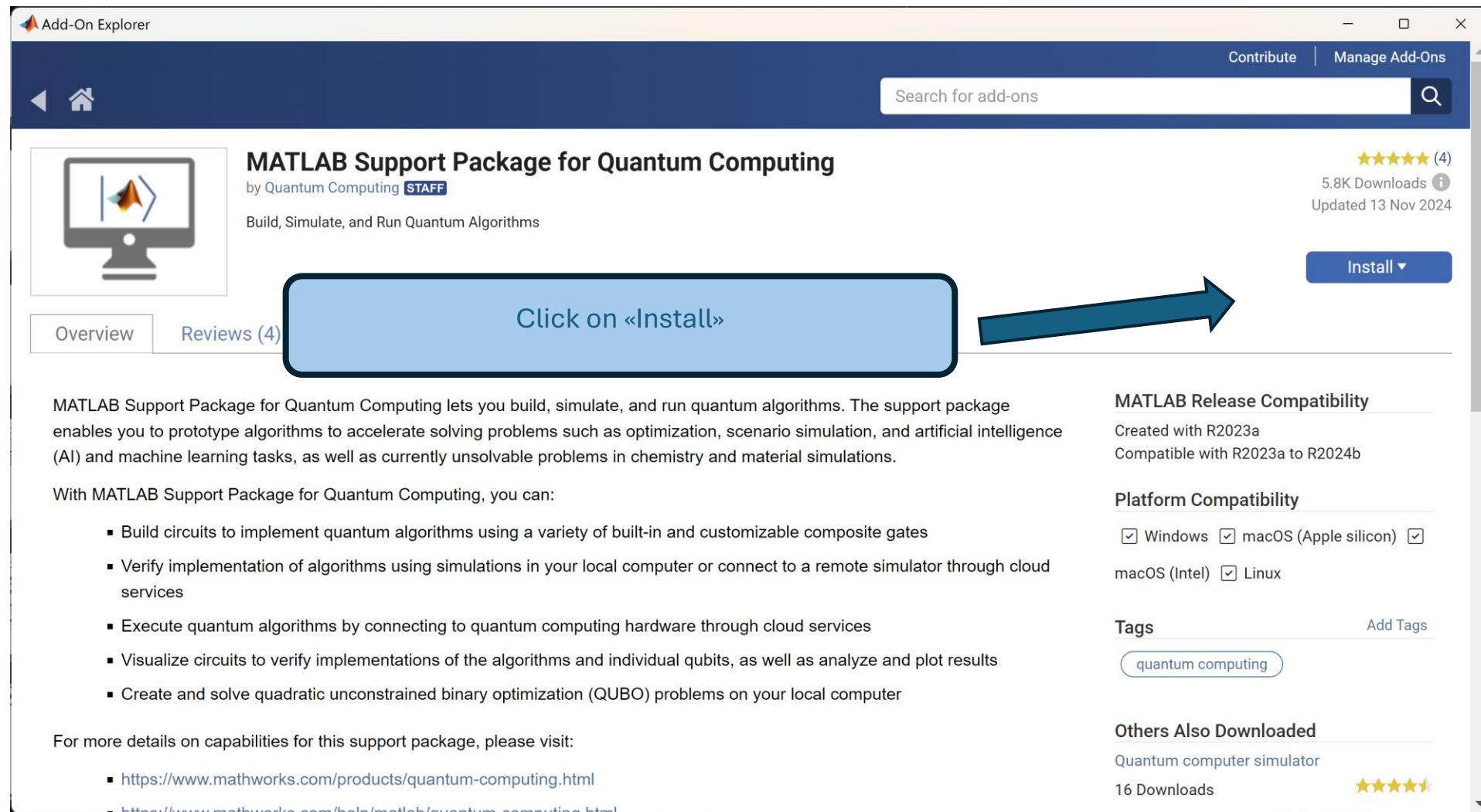


Open MATLAB and click on «Get Add-Ons»

Install MATLAB Support Package for QC



Install MATLAB Support Package for QC



The screenshot shows the MATLAB Add-On Explorer window. The title bar reads "Add-On Explorer". The top navigation bar includes "Contribute" and "Manage Add-Ons" links, and a search bar labeled "Search for add-ons". The main content area displays the "MATLAB Support Package for Quantum Computing" by Quantum Computing (STAFF). The package description is "Build, Simulate, and Run Quantum Algorithms". The package has a 4-star rating (4 stars), 5.8K Downloads, and was updated on 13 Nov 2024. A blue "Install" button is visible. A blue box with the text "Click on «Install»" and a blue arrow points to the "Install" button. The package details section includes a description, a list of capabilities, and compatibility information.

MATLAB Support Package for Quantum Computing
by Quantum Computing **STAFF**
Build, Simulate, and Run Quantum Algorithms

★★★★★ (4)
5.8K Downloads
Updated 13 Nov 2024

Install

Click on «Install»

MATLAB Support Package for Quantum Computing lets you build, simulate, and run quantum algorithms. The support package enables you to prototype algorithms to accelerate solving problems such as optimization, scenario simulation, and artificial intelligence (AI) and machine learning tasks, as well as currently unsolvable problems in chemistry and material simulations.

With MATLAB Support Package for Quantum Computing, you can:

- Build circuits to implement quantum algorithms using a variety of built-in and customizable composite gates
- Verify implementation of algorithms using simulations in your local computer or connect to a remote simulator through cloud services
- Execute quantum algorithms by connecting to quantum computing hardware through cloud services
- Visualize circuits to verify implementations of the algorithms and individual qubits, as well as analyze and plot results
- Create and solve quadratic unconstrained binary optimization (QUBO) problems on your local computer

For more details on capabilities for this support package, please visit:

- <https://www.mathworks.com/products/quantum-computing.html>
- <https://www.mathworks.com/help/matlab/quantum-computing.html>

MATLAB Release Compatibility
Created with R2023a
Compatible with R2023a to R2024b

Platform Compatibility

☒ Windows ☒ macOS (Apple silicon) ☒
macOS (Intel) ☒ Linux

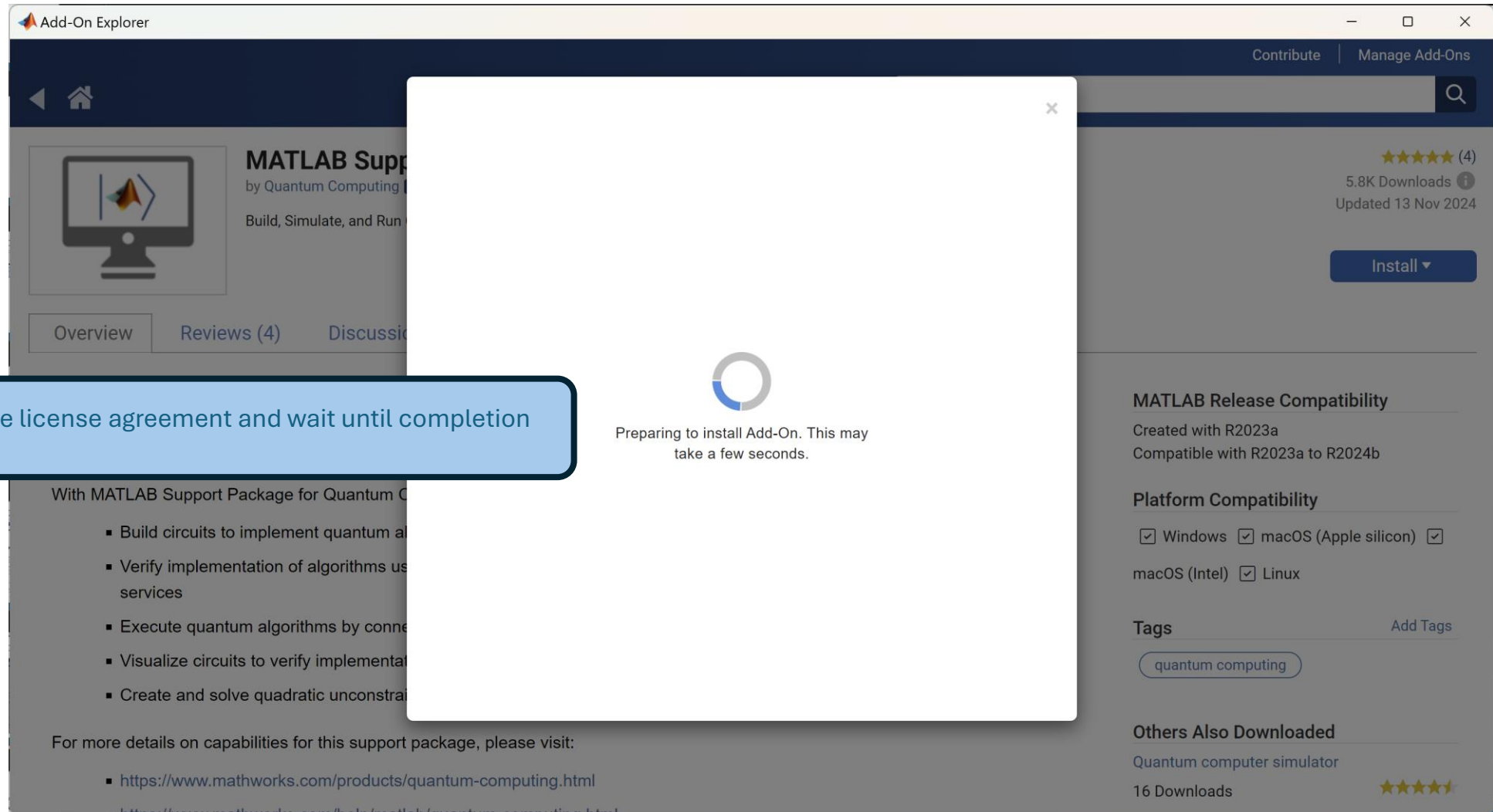
Tags [Add Tags](#)

quantum computing

Others Also Downloaded

Quantum computer simulator
16 Downloads
★★★★★

Install MATLAB Support Package for QC



MATLAB OnRamp

In case you don't know how to use MATLAB, please follow this easy tutorial: [link](#)

You will find useful material and basics on programming with MATLAB.

Sign up to IBM Quantum

The image shows a screenshot of the IBM Quantum login page in a web browser. The browser's address bar displays the URL `https://quantum.ibm.com/login`. A blue arrow points from a text box to the address bar. The page features a dark theme with a navigation bar at the top containing links for 'Dashboard', 'Compute resources', and 'Jobs'. The main content area is split into two sections. The left section, titled 'IBM Quantum', includes a brief description and a 'Documentation' link. The right section, titled 'Sign in to IBM Quantum', contains a large blue button labeled 'Continue with IBMId' and a link for 'New to IBM Quantum? Create an IBMId'. A second blue arrow points from a text box to this link. The footer of the page includes links for 'Terms', 'Privacy', 'Cookie preferences', and 'Support', along with system icons for brightness, window, and theme.

Go to [this link](https://quantum.ibm.com/login)

Sign in to IBM Quantum

Continue with IBMId

New to IBM Quantum?
[Create an IBMId](#)

Having trouble signing in?
Try signing in with an IBMId. If you are still having issues, contact the IBMId help desk.

Create an IBMId

Sign up to IBM Quantum

Registrati per My IBM account

https://www.ibm.com/account/reg/it-it/signup?formid=urx-19776&target=https%3A%2F%2Flogin.ibm.com%2Foidc%2Fendpoint%2Fdefault%2Fauthorize%3Fqsld%3D773bdf3...

IBM

Benvenuto in IBM

Crea un account per accedere a versioni di prova, demo e servizi.

Crea un IBMid

Si dispone già di un account IBM? [Login](#)

Informazioni account

Riempimento automatico con LinkedIn

Email ⓘ

L'indirizzo email diventerà l'IBMid da utilizzare per accedere a IBM.com.

Nome

Cognome

Password

Paese o regione di residenza

Italia

Stato o provincia

Seleziona stato

Insert your data. Specify that you are a student

Sign up to IBM Quantum

IBM Quantum Platform | Dashboard | Compute resources | Jobs

Last step! Before you get started,
Tell us a little more about yourself

First name *

Enter your first name

Field required

Last name *

Enter your last name

Field required

Your company or institution *

Politecnico di Milano

Do not use abbreviations to avoid issues with your account. If you are not affiliated with a company or institution, please write 'Unaffiliated.'

What is your familiarity with quantum?

Hmm what's a qubit?

What would you like to use IBM Quantum for?

For event-specific access, please specify the event in the field below.

Insert your data. Specify that your institution is Politecnico di Milano

IBM Quantum Dashboard

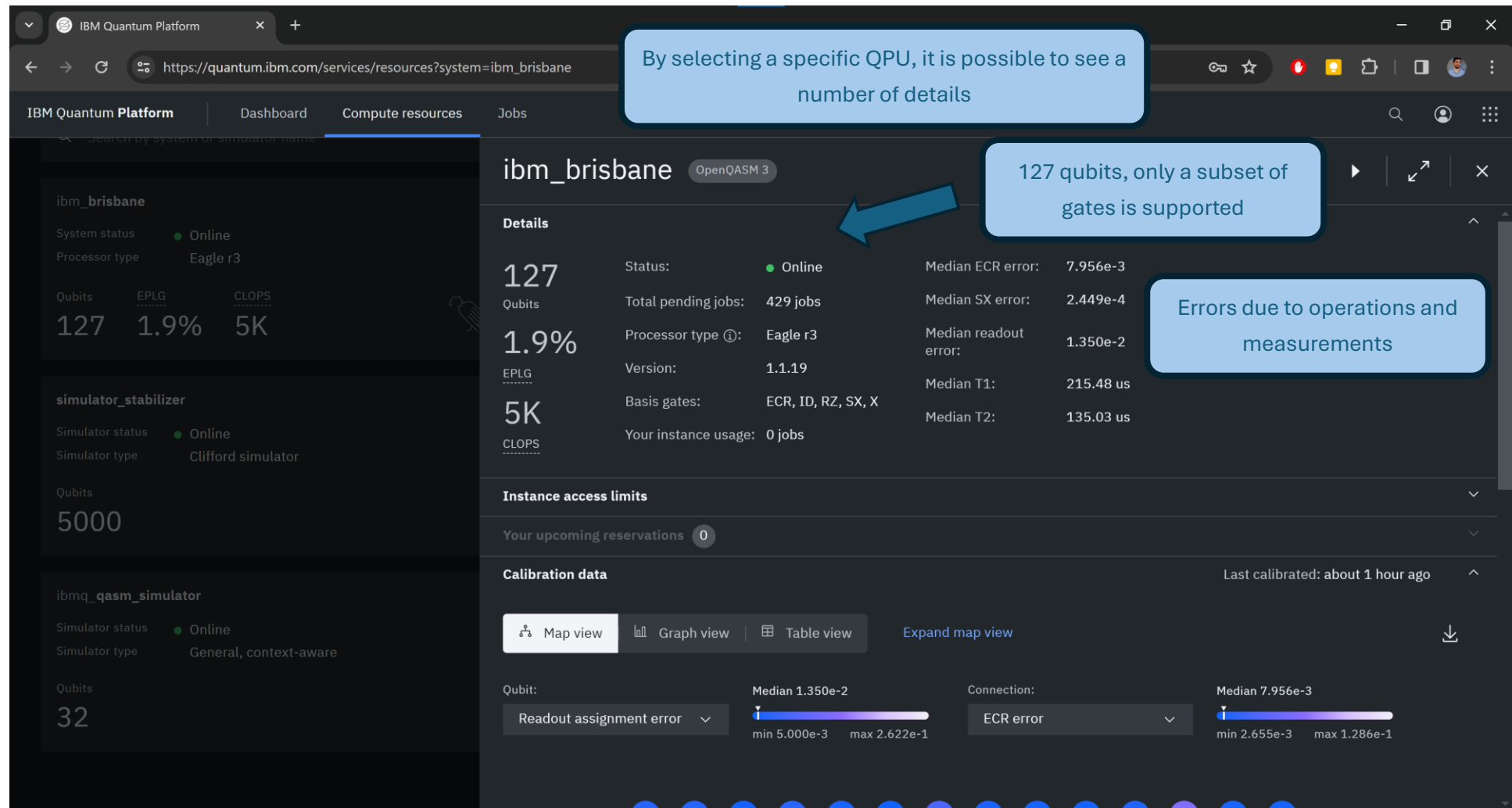
The screenshot shows the IBM Quantum Platform dashboard in a web browser. The browser's address bar displays 'quantum.ibm.com'. The dashboard's navigation bar includes links for 'IBM Quantum Platform', 'Dashboard' (which is selected), 'Functions', 'Compute resources', and 'Workloads'. A search bar and a user profile icon are also present. The main header area features the user's name 'Marco Venere' and the 'IBM Quantum Platform' logo. A blue callout box with an arrow pointing to the 'Compute resources' link contains the text 'Click here to see available quantum computers and their information'. Below the header, there is a section for 'API Token' with a button to 'Token to use for access with MATLAB', which is highlighted by another blue callout box with an arrow pointing to it. The dashboard also displays a 'Premium plan' section, 'Instance usage' statistics (This cycle: Oct 23, 2024 - Nov 20, 2024), and a 'Recent workloads' section with a 'Get started' button. On the right side, there is a 'What's new' section with links to a blog and a product update. At the bottom, there are sections for 'Instance QPUs' (showing '2' and 'All QPUs'), 'Documentation' (with a search bar and 'Hello World' text), and 'Learning' (with a 'Featured course' and 'Catalog' link). A 'Snipping Tool' window is visible in the bottom right corner, indicating that a screenshot was taken.

IBM Quantum Dashboard

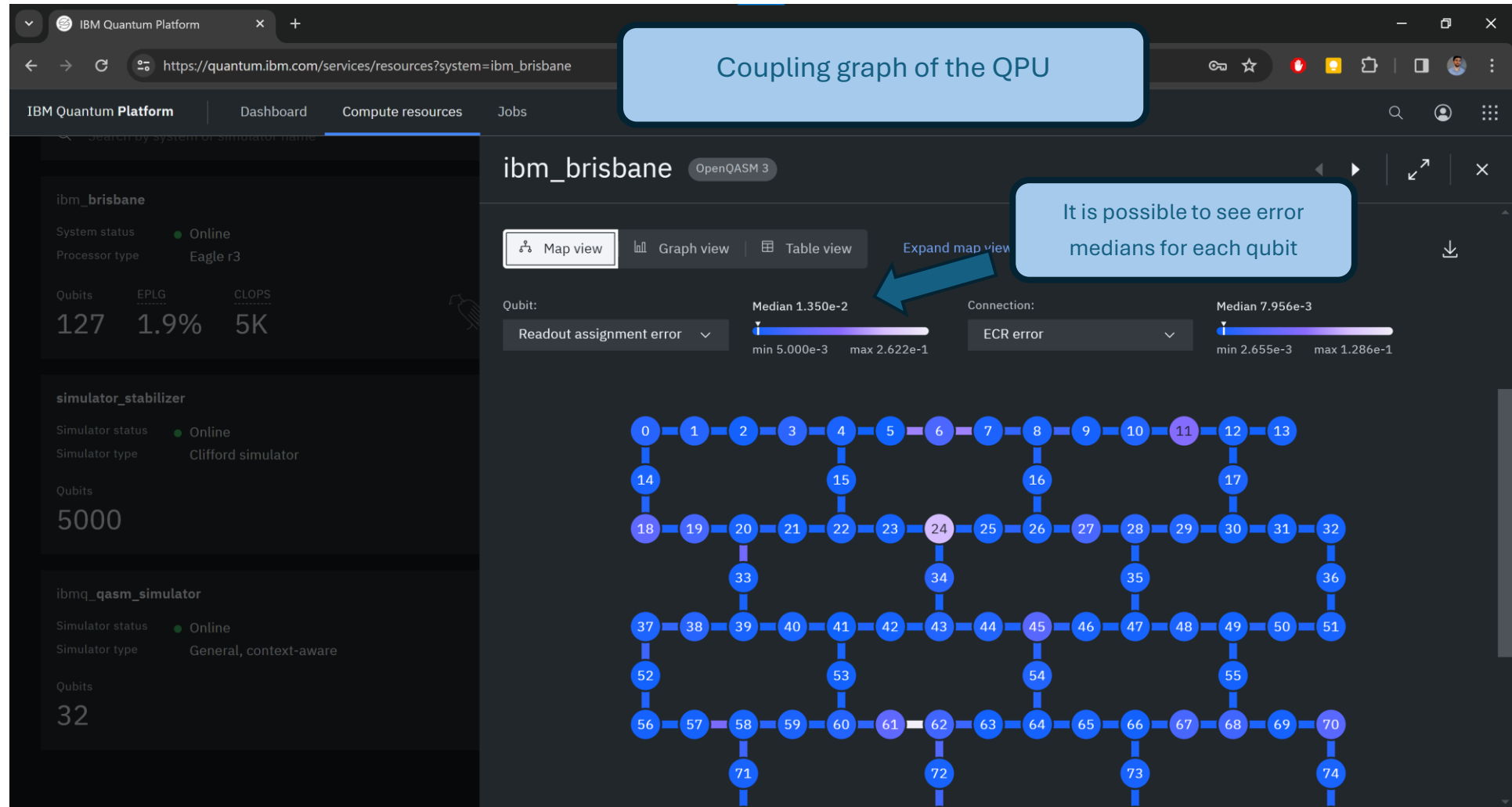
The screenshot displays the IBM Quantum Platform interface. A blue callout box at the top right states: "Here you can see all available Quantum Computers". The main heading is "Compute resources", with a subtext explaining access plans. Below this, there are tabs for "Instance resources", "All systems", and "All simulators". A message indicates access to resources with instance "ibm-q/open/main.". A search bar and a dropdown menu "Your systems & simulators (8)" are present. The resources are listed in a grid:

Resource Name	Status	Processor Type	Qubits	EPLG	CLOPS
ibm_brisbane	Online	Eagle r3	127	1.9%	5K
ibm_osaka	Online	Eagle r3	127	2.8%	5K
ibm_kyoto	Online	Eagle r3	127	3.6%	5K
simulator_stabilizer	Online	Clifford simulator	-	-	-
simulator_mps	Online	Matrix Product State	100	-	-
simulator_extended_stabilizer	Online	Extended Clifford (e.g. Clifford+T)	62	-	-

IBM Quantum Dashboard



IBM Quantum Dashboard



IBM Quantum Dashboard

The screenshot shows the 'Jobs' page of the IBM Quantum Platform. The browser address bar displays 'https://quantum.ibm.com/jobs'. The navigation bar includes 'Dashboard', 'Compute resources', and 'Jobs'. The main heading is 'Jobs', followed by a description: 'Track the status and results of the jobs you have run on IBM Quantum resources via the instance `ibm-q/open/main`.' Below this is a search bar and a table with columns: Job Id, Session Id, Status, Created, Completed, Program, Compute resource, Usage, and Tags. The table is currently empty, showing a message: 'You do not currently have any jobs. Once you have run a circuit on a system or simulator, you can track the job's status and view details from this table.' Three blue callout boxes provide additional context: 'Here you can find all your jobs', 'Look for <<Workloads>> in the last version of the website', and 'Every job represents a circuit you have run and its output'.

Jobs

Track the status and results of the jobs you have run on IBM Quantum resources via the instance `ibm-q/open/main`.

Search jobs by ID, name or tag

Job Id	Session Id	Status	Created	Completed	Program	Compute resource	Usage	Tags
You do not currently have any jobs								

Once you have run a circuit on a system or simulator, you can track the job's status and view details from this table.

Here you can find all your jobs

Look for <<Workloads>> in the last version of the website

Every job represents a circuit you have run and its output

IBM Quantum Dashboard

Jobs | IBM Quantum Platform

https://quantum.ibm.com/jobs

IBM Quantum Platform | Dashboard | Compute resources | **Jobs**

Jobs

Track the status and results of the jobs you have run on IBM Quantum resources via the instance **ibm-q/open/main**.

Used
0ms used / 10m

Search jobs by ID, name or tag

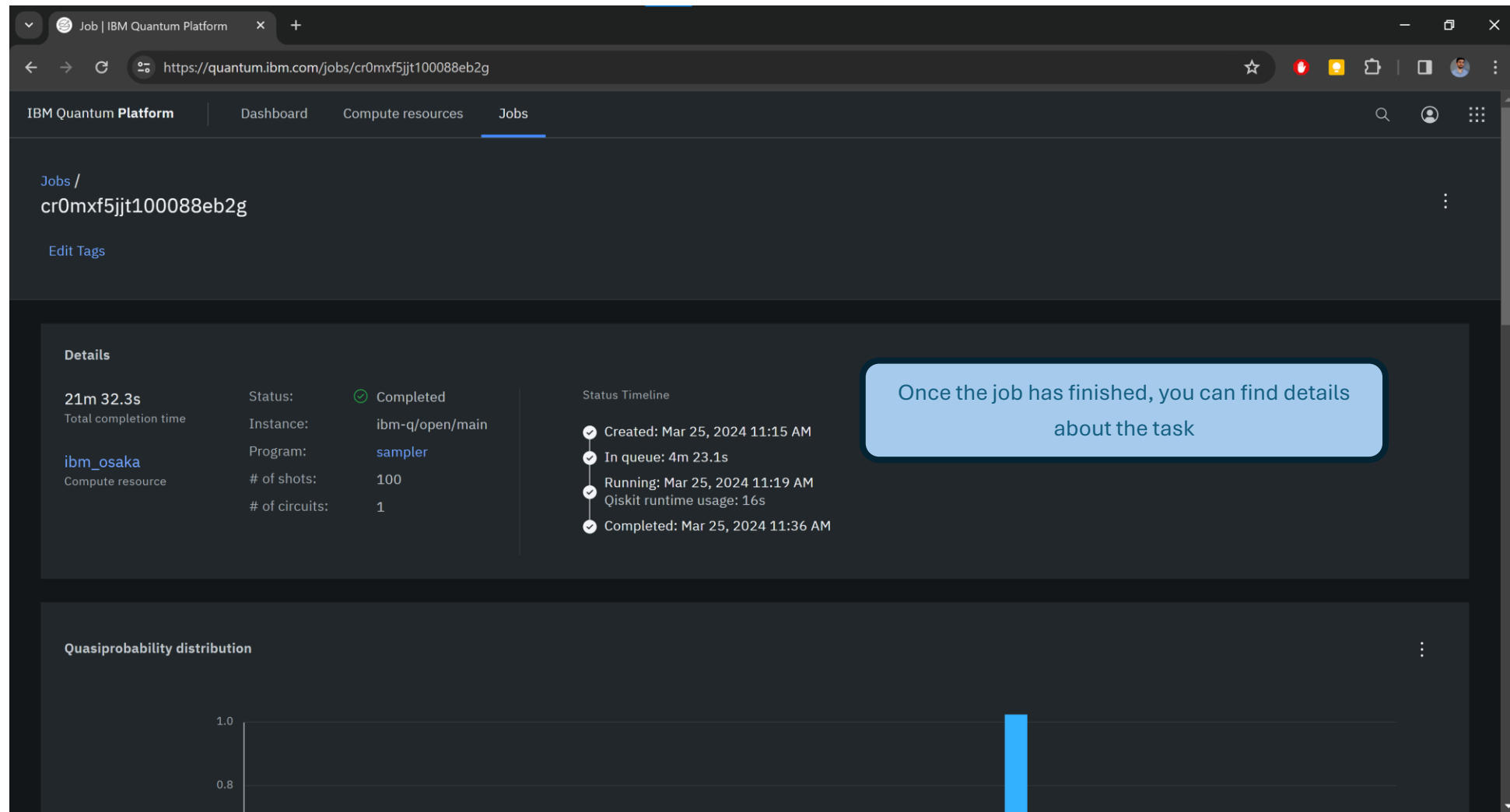
All statuses

<input type="checkbox"/>	Job Id	Session Id	Status	Created	Completed	Program	Compute resource	Usage	Tags
<input type="checkbox"/>	cqyrjk2s9z7g00...		Queued Est. wait: 2 hours	22 minutes ago		sampler	ibm_osaka Queue position: 18	Est. 31.1s	

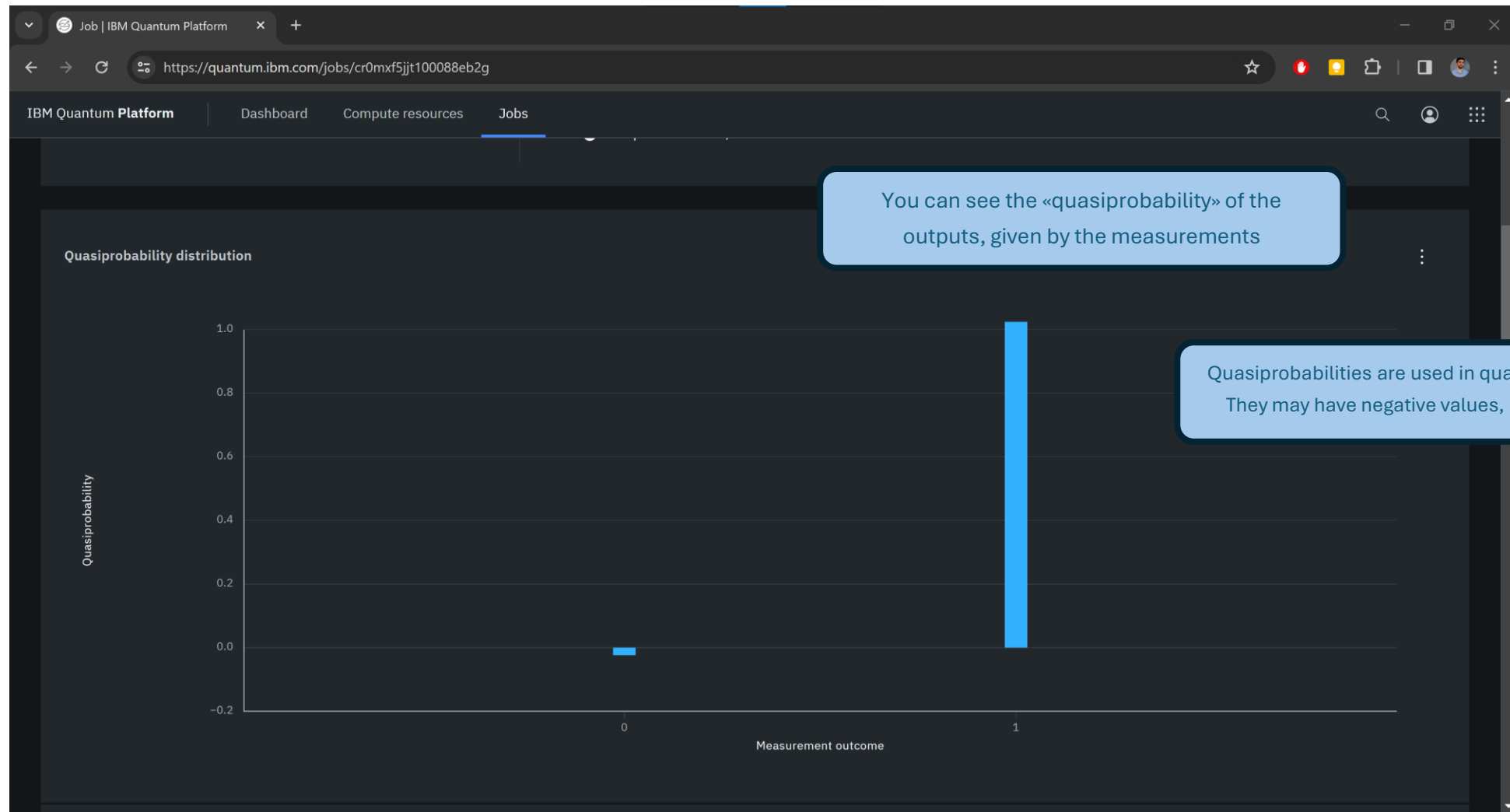
Items per page: 10 | 1-1 of 1 items | 1 of 1 pages

Terms | Privacy | Cookie preferences | Support

IBM Quantum Dashboard



IBM Quantum Dashboard



IBM Quantum Dashboard

The screenshot displays the IBM Quantum Platform interface. The browser address bar shows the URL `https://quantum.ibm.com/jobs/cr0mxf5jtt100088eb2g`. The navigation bar includes links for "IBM Quantum Platform", "Dashboard", "Compute resources", and "Jobs". The "Jobs" tab is active, showing a "Measurement outcome" section. Below this, there are two tabs for the circuit representation: "Qasm" (selected) and "Qiskit". A blue callout box states: "For every job, you can also see the circuit representation in QASM, which is Quantum Assembly (a common standard)."

The "Original circuit" section displays the following QASM code:

```
1 OPENQASM 3.0;
2 include "stdgates.inc";
3
4 qubit[1] q;
5 bit[1] c;
6
7 x q[0];
8 c = measure q;
```

The "Transpiled circuit" section displays the following QASM code:

```
1 OPENQASM 2.0;
2 include "qelib1.inc";
3 qreg q[127];
4 creg c[1];
5 x q[0];
6 measure q[0] -> c[0];
7
```

At the bottom, there is a link that says "Open in composer".

Now your setup should be working!

Next Steps:

1. Create our first Quantum Circuits
2. Simulate them classically
3. Run them on real quantum hardware

Create our first Quantum Circuits

We need to create a **quantumCircuit** object....

Docs here: [quantumCircuit](#)

Let's do it now with a LiveScript!

More Quantum Algorithms

We are also going to see some examples of famous quantum algorithms:

- Quantum Teleportation
- Quantum Fourier Transform

Quantum Teleportation

Recap: Alice and Bob share a pair of entangled qubits $|\Phi^+\rangle_{AB}$.

Alice also possesses a qubit $|\psi\rangle_{A'} = \alpha|0\rangle_{A'} + \beta|1\rangle_{A'}$:

$$|\psi\rangle_{A'} |\Phi^+\rangle_{AB} = (\alpha|0\rangle_{A'} + \beta|1\rangle_{A'}) \frac{|00\rangle_{AB} + |11\rangle_{AB}}{\sqrt{2}}$$

Alice measures her two qubits using the Bell states, and Bob's qubit becomes one of

$$|\psi\rangle_B, Z|\psi\rangle_B, X|\psi\rangle_B, XZ|\psi\rangle_B$$

Alice sends two classical bits and Bob reconstructs $|\psi\rangle_B$.

A whole qubit has been teleported using a pair of entangled qubits and two classical bits.

Quantum Teleportation

Let's implement it on MATLAB!

We need:

- A circuit with 3 qubits
- An initialization with entanglement + generic qubit $|\psi\rangle$
- A Bell measurement for Alice's qubits
- The application of Z and X gates conditioned by Alice measurement

Quantum Fourier Transform

The Quantum Fourier Transform is the quantum analogue of the Discrete Fourier Transform (DFT).

It's very useful for a number of quantum algorithms, e.g., Shor's algorithm for integer factorization, discrete logarithm, quantum phase estimation, and algorithms for the hidden subgroup problem.

There is a computational advantage in computing the QFT: indeed, we can apply a DFT on 2^n amplitudes by using only $O(n^2)$ Hadamard gates and controlled phase shift gates. The classical approach would instead require $O(n2^n)$ operations.

Quantum Fourier Transform

Classical DFT: it maps a vector $(x_0, x_1, \dots, x_{N-1}) \in \mathbb{C}^N$ to another vector $(y_0, y_1, \dots, y_{N-1}) \in \mathbb{C}^N$

$$y_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n \omega_N^{-nk}, \omega_N = e^{\frac{2\pi i}{N}}, k = 0, 1, 2, \dots, N-1$$

QFT: it maps a quantum state $|x\rangle = \sum_{i=0}^{N-1} x_i |i\rangle$ to another quantum state $|y\rangle = \sum_{i=0}^{N-1} y_i |i\rangle$, where $N = 2^n$, which means that the state is spread across n different qubits.

$$y_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n \omega_N^{nk}, \omega_N = e^{\frac{2\pi i}{N}}, k = 0, 1, 2, \dots, N-1$$

The sign of the exponential varies based on different conventions. ω_N^{nk} represents a rotation.

Quantum Fourier Transform

For example, if $|x\rangle$ is a basis state, we can define the whole QFT operation as:

$$QFT: |x\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \omega_N^{xk} |k\rangle$$

where xk is the scalar product between the bitstring x and the bitstring k .

E.g., $x = 11001$ and $k = 10011 \rightarrow xk = 1 \cdot 1 + 1 \cdot 0 + 0 \cdot 0 + 0 \cdot 1 + 1 \cdot 1$

Inverse Quantum Fourier Transform

The inverse of the QFT is also defined:

$$x_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y_n \omega_N^{-nk}, \quad n = 0, 1, 2, \dots, N-1$$

Notice the difference in the sign of the phase.

Practical Implementation of QFT

Given n qubits, whose state is given by a vector of 2^n components, the computation of the QFT can be given by using the following $2^n \times 2^n$ matrix:

$$\begin{pmatrix} 1 & 1 & 1 & 1 & \dots & 1 \\ 1 & \omega & \omega^2 & \omega^3 & \dots & \omega^{N-1} \\ 1 & \omega^2 & \omega^4 & \omega^6 & \dots & \omega^{2(N-1)} \\ 1 & \omega^3 & \omega^6 & \omega^9 & \dots & \omega^{3(N-1)} \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 1 & \omega^{N-1} & \omega^{2(N-1)} & \omega^{3(N-1)} & \dots & \omega^{(N-1)(N-1)} \end{pmatrix}$$

On a practical level, this circuit can be implemented by using a number of Hadamard gates and controlled rotation gates. Let's look at it on MATLAB...

Thank you for your attention!

Quantum Computing A Practical Perspective

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Politecnico di Milano

