

# Quantum Computing

## A Practical Perspective

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Politecnico di Milano



# Agenda

- Lecture 1 → Theory Recap on Quantum Computing
- Lecture 2 → Initial Setup and First Experiments
- Lecture 3 → Grover's Algorithm
- Lecture 4 → Combinatorial Optimization
- Lecture 5 → VQE, QNN, QMC
- Lecture 6 → Quantum Error Correction & Mitigation – Projects Presentation

# 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

Mathworks Matlab

Matlab is an interactive language and environment for numerical computation, visualization, and programming. It allows you to analyze data, develop algorithms, create models and applications.

Operating system: Windows, Linux, macOS  
System requirements

The licenses are "educational" editions, the use of the application packages is strictly limited to the University's institutional activities, thus excluding any use for personal, professional purposes and for profit.

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

- Create a Mathworks account
- 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.

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Create a MathWorks Account

# Get a license

Mathworks Matlab – University Politecnico di Milano – Accesso https://it.mathworks.com/academia/tah-portal/politecnico-di-milano-30924786.html

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

Esploра 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

I dati raccolti verranno trattati secondo la nostra [Privacy Policy](#).

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.

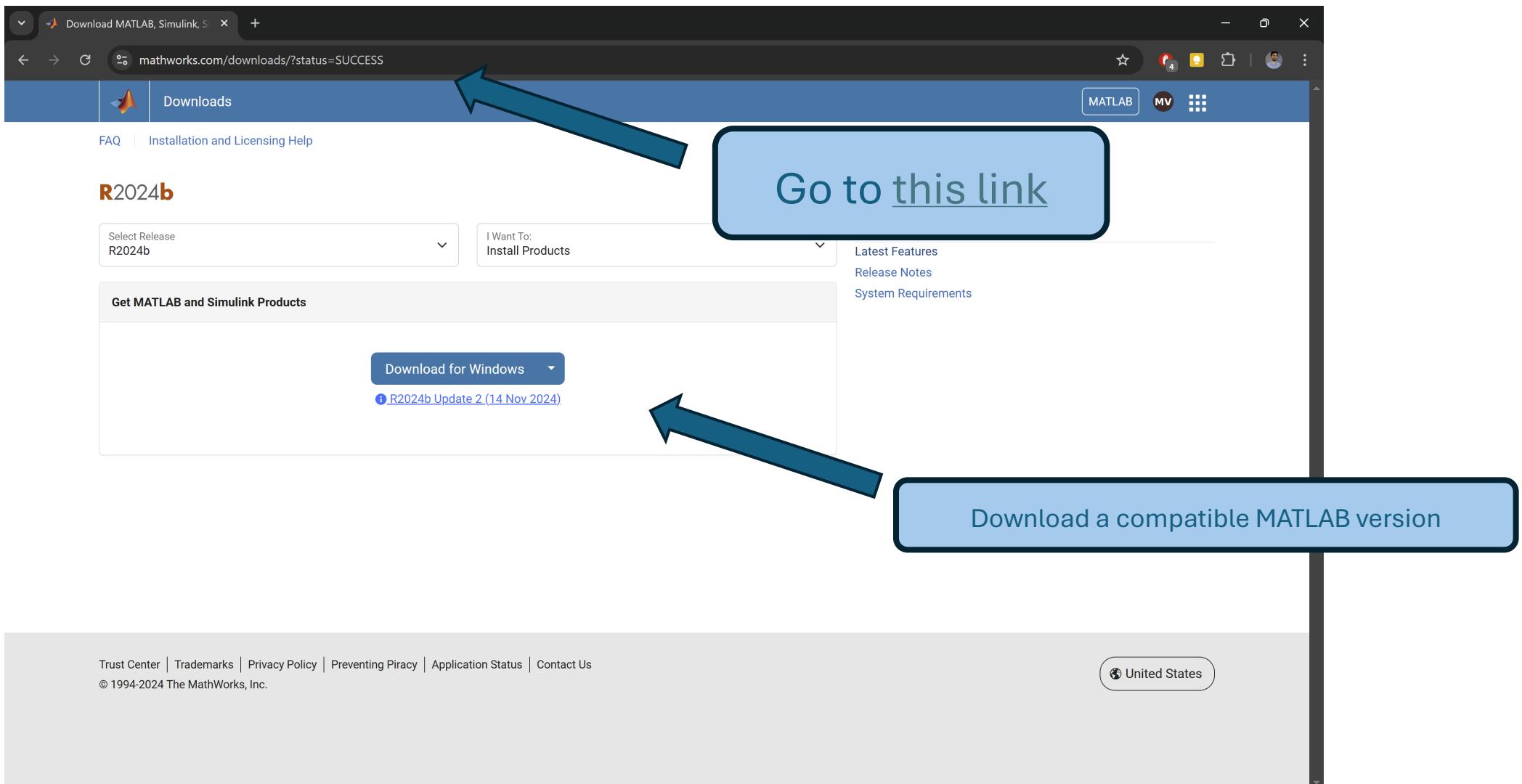
Vedi i corsi autogestiti | Ricerca di documentazione, esempi e video

Click here to login

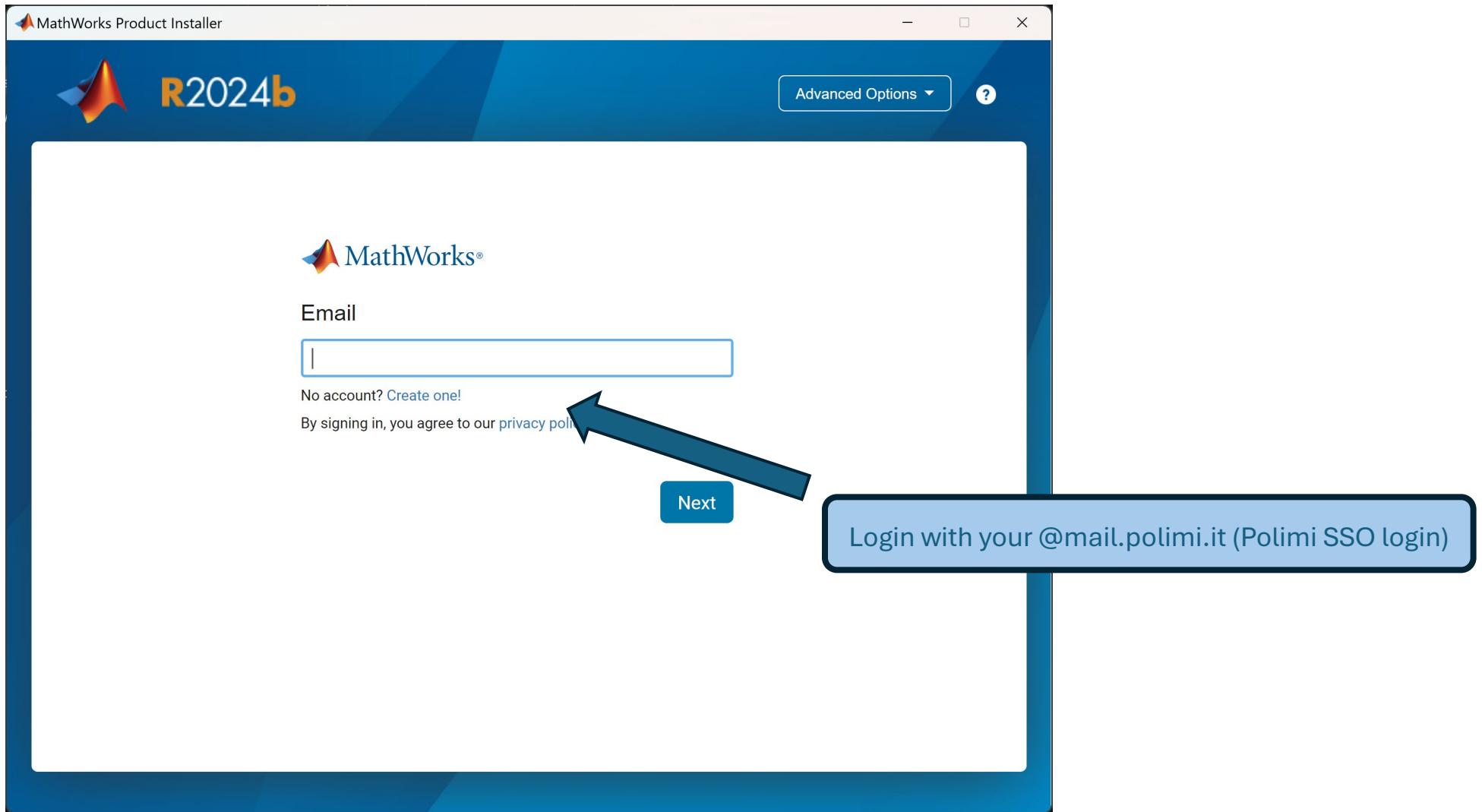
# Get a license

- 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

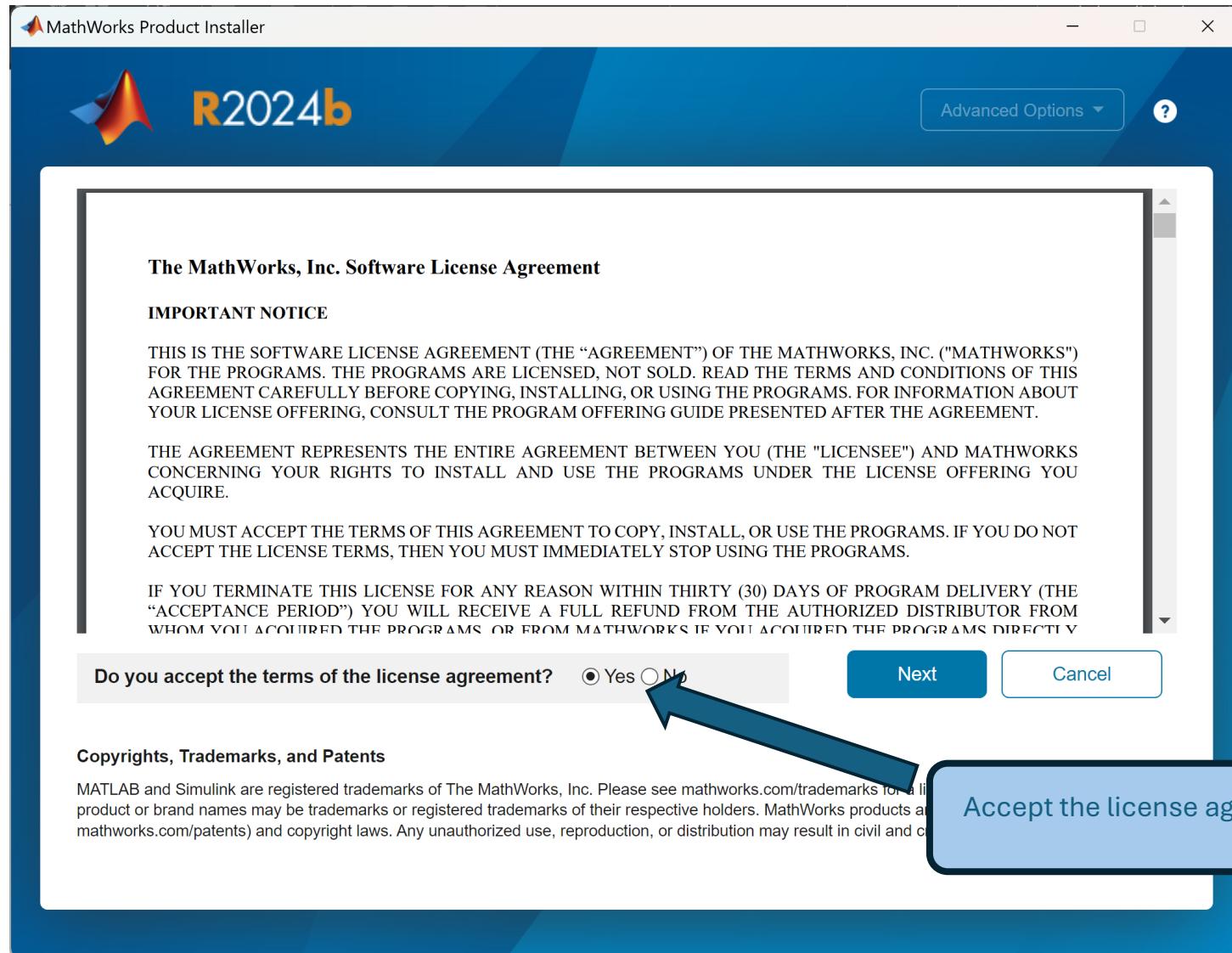
# Install MATLAB R2024b



# Install MATLAB R2024b



# Install MATLAB R2024b

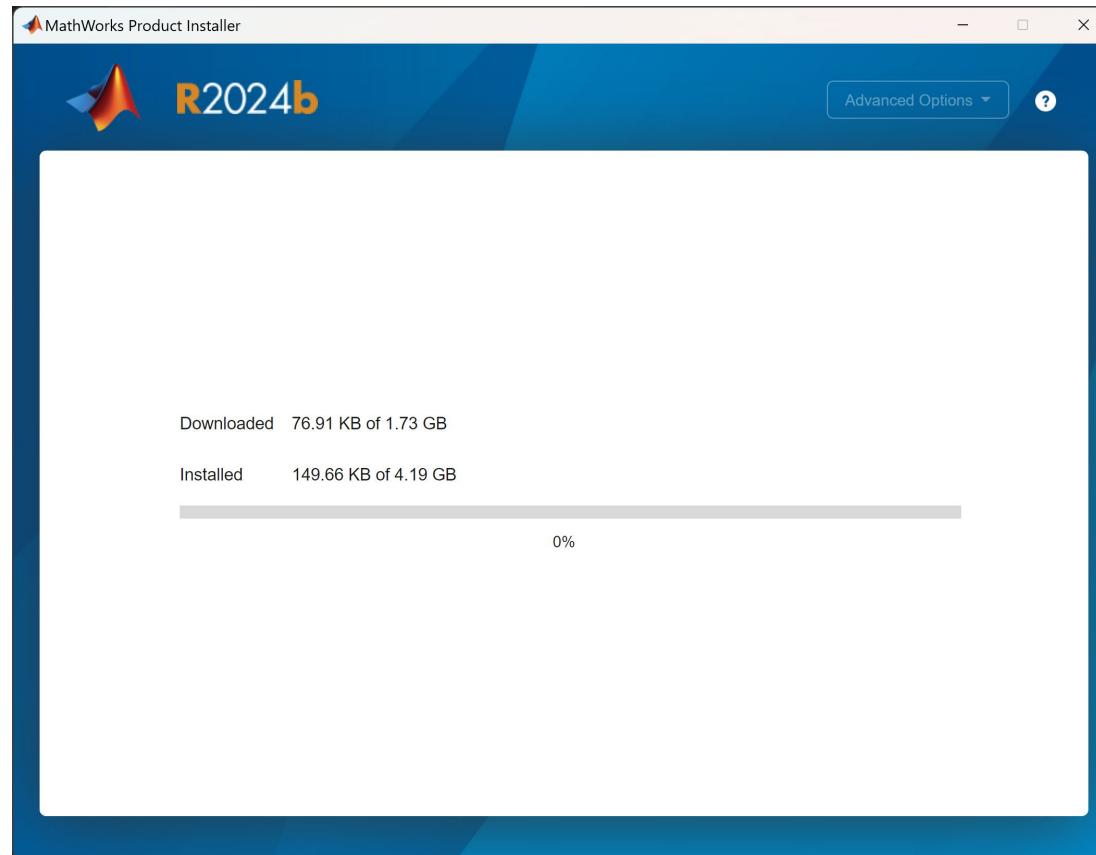


# Install MATLAB R2024b

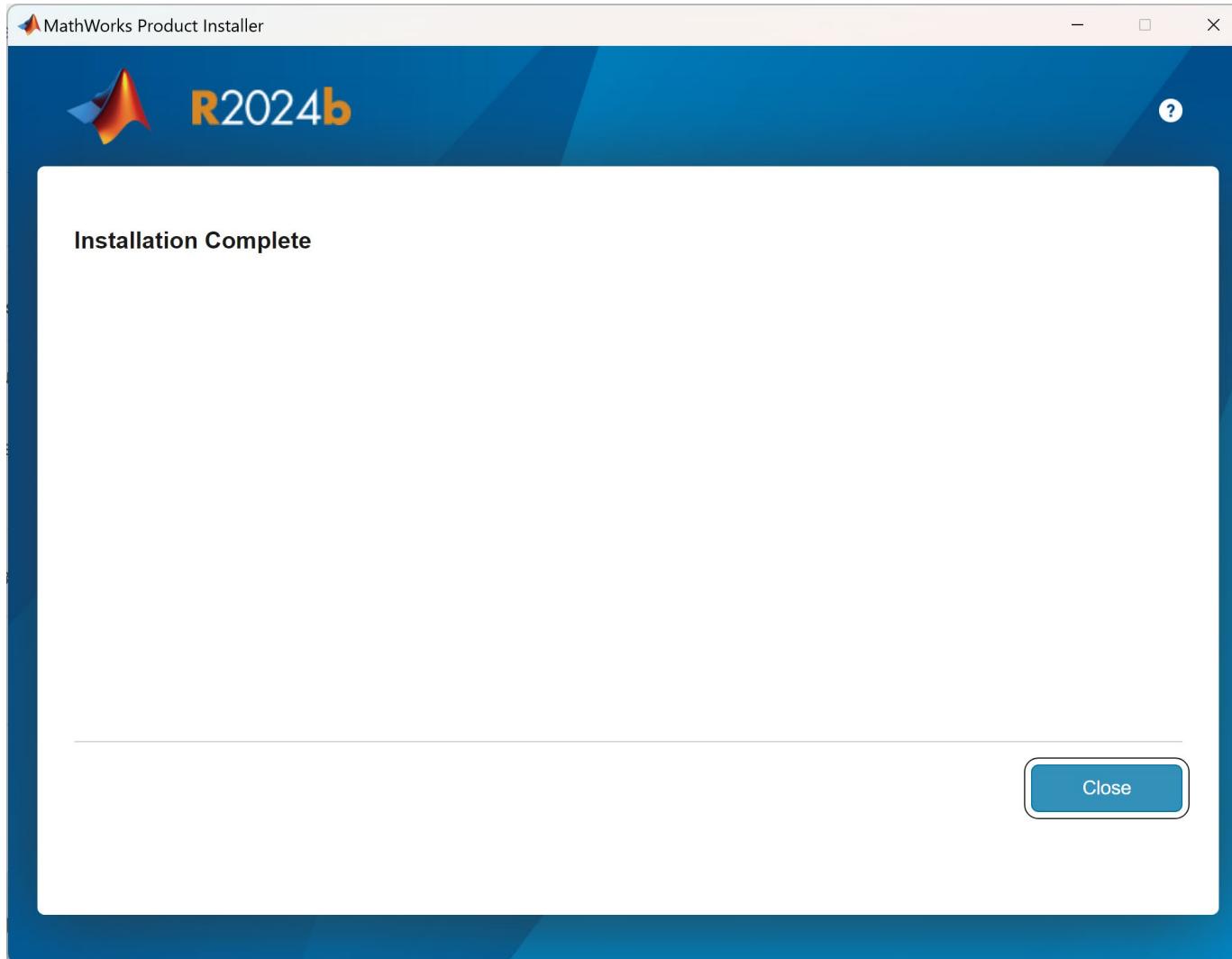
- Press “Next” a bunch of times and then “Begin Install”

# Install MATLAB R2024b

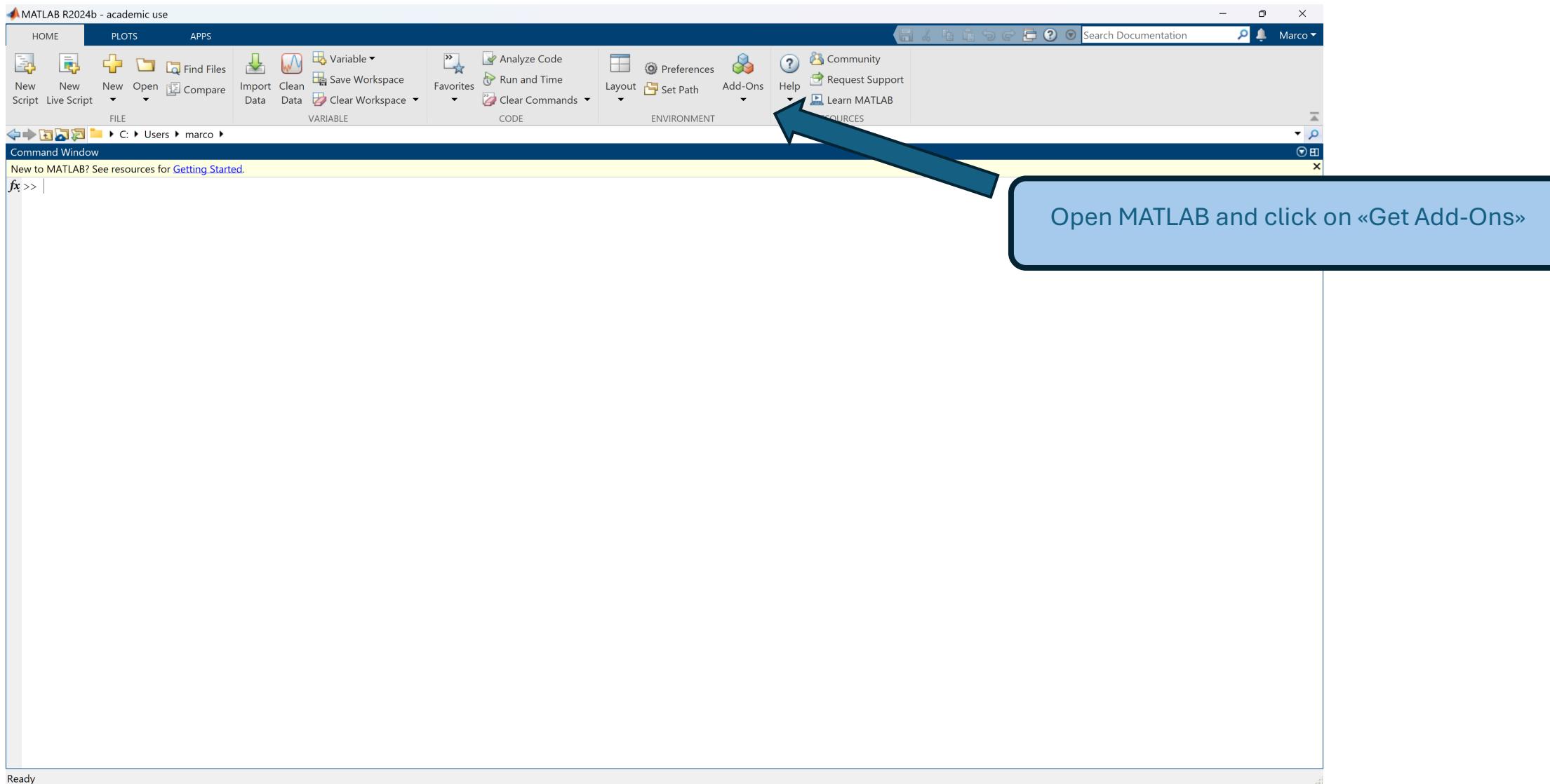
- Press “Next” a bunch of times and then “Begin Install”



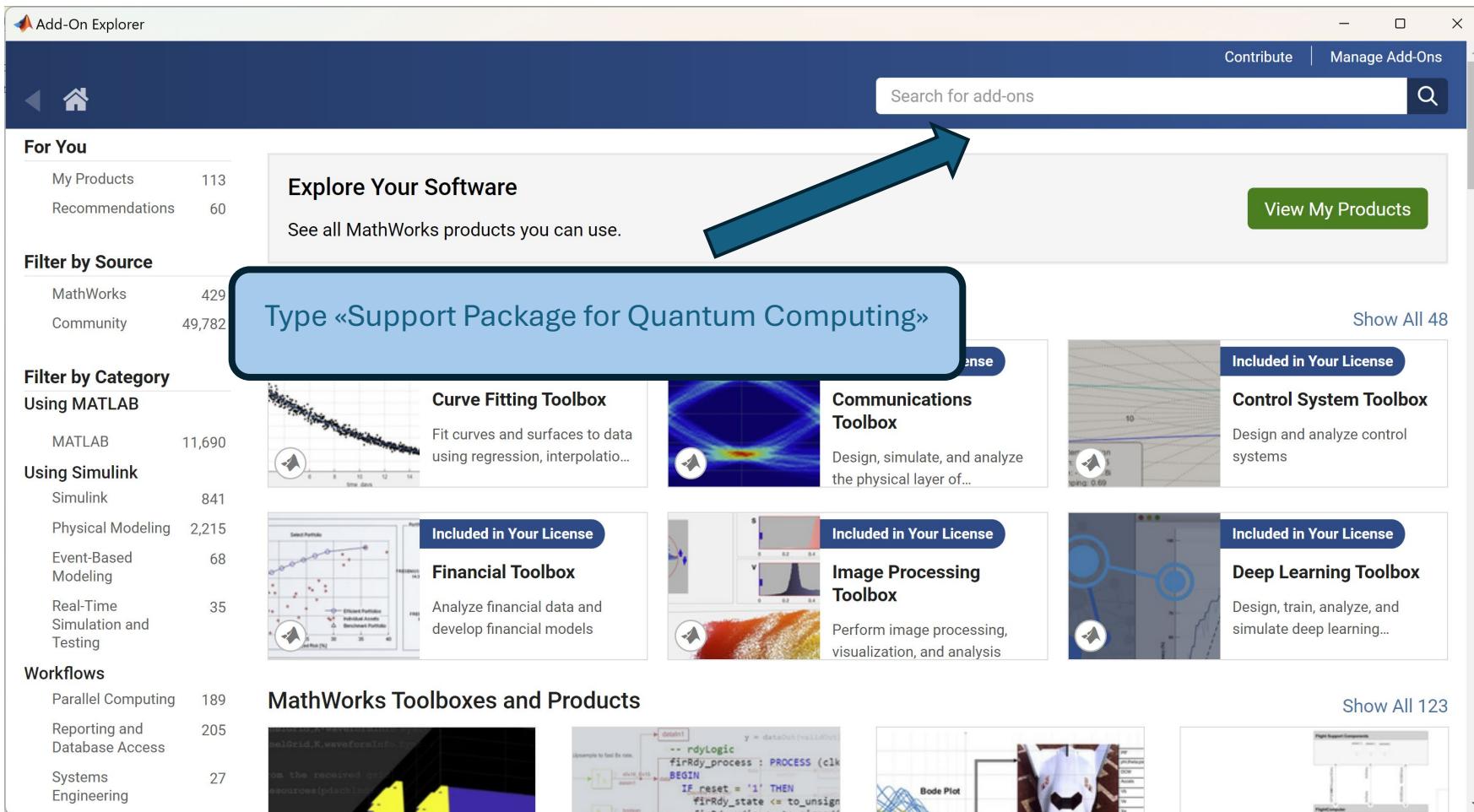
# Install MATLAB R2024b



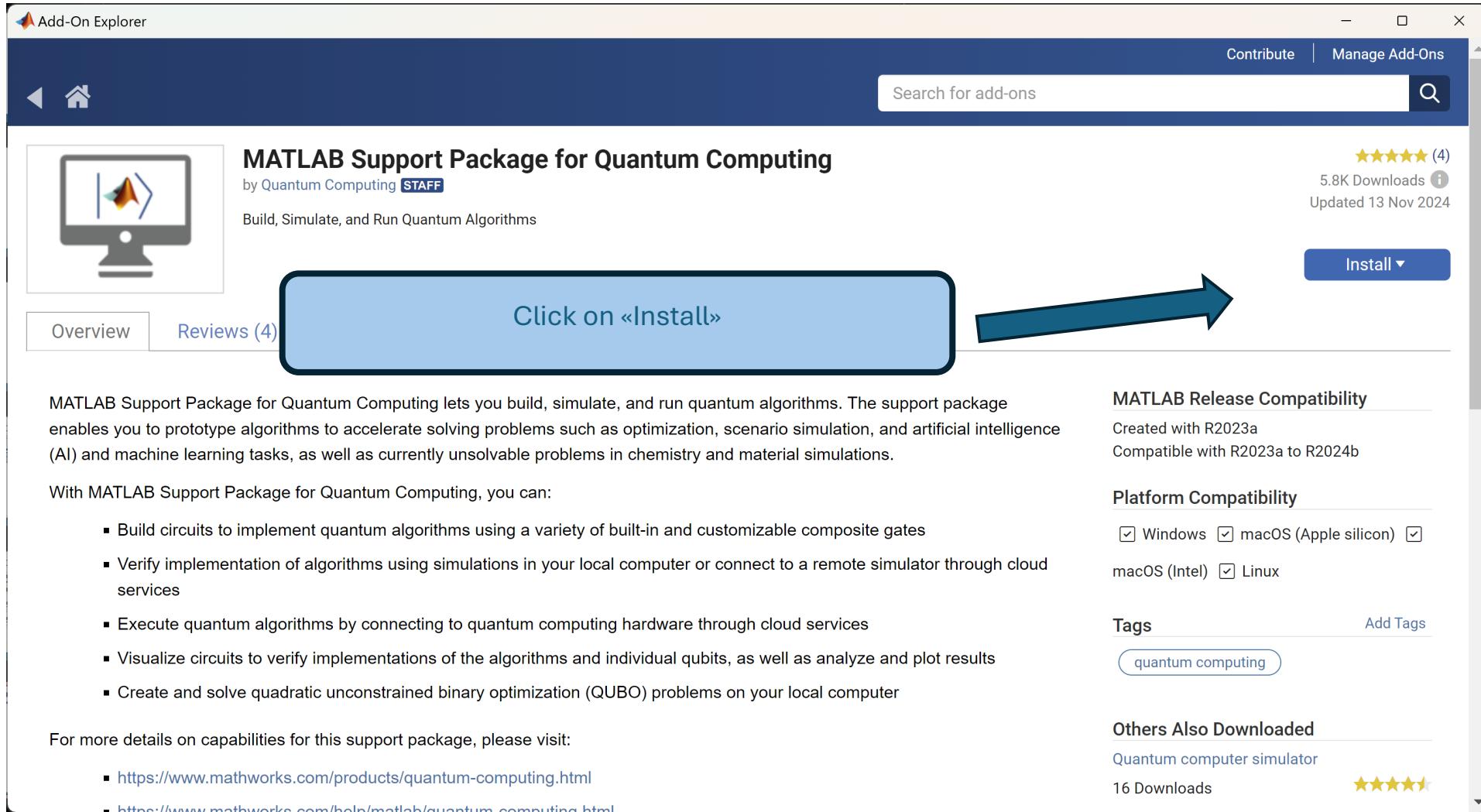
# Install MATLAB Support Package for QC



# Install MATLAB Support Package for QC



# Install MATLAB Support Package for QC



The screenshot shows the MATLAB Add-On Explorer interface. In the center, there is a card for the "MATLAB Support Package for Quantum Computing" by Quantum Computing STAFF. The card includes a thumbnail of a MATLAB interface, a brief description ("Build, Simulate, and Run Quantum Algorithms"), and a summary section. A large blue callout bubble with a black border and a white background is overlaid on the card, containing the text "Click on «Install»". A thick blue arrow points from the bottom right of the callout towards the "Install" button on the card. To the right of the card, there are sections for "MATLAB Release Compatibility" (Created with R2023a, Compatible with R2023a to R2024b), "Platform Compatibility" (checkboxes for Windows, macOS (Apple silicon), macOS (Intel), and Linux), and "Tags" (quantum computing). Below the card, there's a section for "Others Also Downloaded" with a "Quantum computer simulator" entry, 16 Downloads, and a 5-star rating.

Search for add-ons  Q

Add-On Explorer

Contribute | Manage Add-Ons

**MATLAB Support Package for Quantum Computing**

by Quantum Computing STAFF

Build, Simulate, and Run Quantum Algorithms

5.8K Downloads i 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](https://www.mathworks.com/help/matlab/quantum_computing.html)

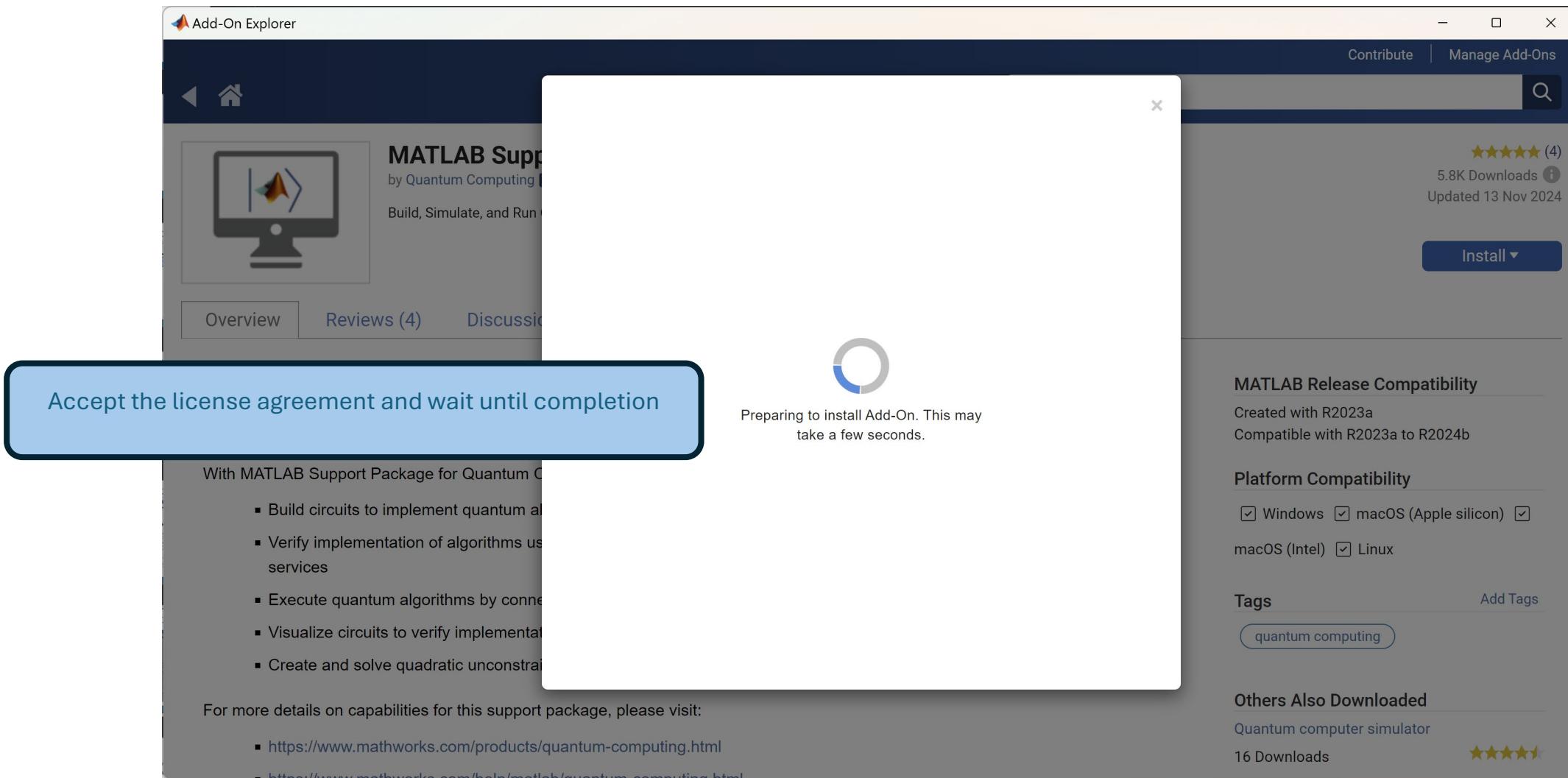
**MATLAB Release Compatibility**  
Created with R2023a  
Compatible with R2023a to R2024b

**Platform Compatibility**  
 Windows  macOS (Apple silicon)   
macOS (Intel)  Linux

**Tags** [Add Tags](#)  
quantum computing

**Others Also Downloaded**  
Quantum computer simulator 5 stars  
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 screenshot shows the IBM Quantum Platform login page at <https://quantum.ibm.com/login>. A blue callout box with the text "Go to this link" has a blue arrow pointing to the URL bar. Another blue callout box with the text "Create an IBMid" has a blue arrow pointing to the "Create an IBMid" button on the right side of the page.

Go to this link

Quantum

Use our suite of applications to support your quantum research and development needs.

</>

**Documentation**

Explore service and API documentation to start working with IBM Quantum resources.

Documentation

This is the new home for all Qiskit and IBM Quantum service documentation. Learn more

Get started with Qiskit  
Run the Hello World

Start  
Set up and install to use Qiskit

Build  
Design and develop quantum circuits

Transpile  
Optimize circuits to efficiently run on hardware

Verify  
Validate and evaluate your quantum circuits

Run  
Execute jobs on quantum hardware

Continue with IBMid

G Q LinkedIn IBM Email

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

The screenshot shows a web browser window for 'Registrazione per My IBM account' at the URL <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...>. The page title is 'IBM'. The main content area has two sections: 'Benvenuto in IBM' on the left and 'Crea un IBMID' on the right. The 'Crea un IBMID' section includes a 'Login' link, an 'Informazioni account' section, and a 'Riempimento automatico con LinkedIn' button. Below these are fields for 'Email', 'Nome', 'Cognome', 'Password', 'Paese o regione di residenza' (set to 'Italia'), and 'Stato o provincia' (set to 'Seleziona stato'). A large blue arrow points from a callout bubble to the 'Cognome' field. The callout bubble contains the text: 'Insert your data. Specify that you are a student'.

Benvenuto in IBM

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

IBM

Crea un IBMID

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

Informazioni account

Riempimento automatico con LinkedIn

Email ①

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

Selezione stato

Insert your data. Specify that you are a student

# Sign up to IBM Quantum

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

A blue callout box with an arrow points from the text "Insert your data. Specify that your institution is Politecnico di Milano" to the "Your company or institution" input field.

# IBM Quantum Dashboard

The screenshot shows the IBM Quantum Platform dashboard. At the top, there is a navigation bar with tabs: IBM Quantum Platform, Dashboard (which is selected), Functions, Compute resources, and Workloads. A blue callout bubble points to the "Compute resources" tab with the text: "Click here to see available quantum computers and their information". Below the navigation bar, a purple header bar displays the name "Marco Venere" and the title "IBM Quantum Platform". A blue callout bubble points to the "API Token" field with the text: "Token to use for access with MATLAB". The main content area includes sections for "Premium plan", "Instance usage" (showing 0ms used, 14s total, 46s remaining), "Recent workloads" (empty), "Get started", "Instance QPUs" (2 available, All QPUs), "Documentation" (Hello World, Open app), "Learning" (Featured course: Quantum Computing in Practice, Catalog, Explore all courses and tutorials), and a "What's new" section with two items: "Blog" (IBM Quantum delivers on performance challenge, 7 days ago) and "Product update" (IBM Quantum Platform interface update, 2 months ago). A screenshot of the Windows taskbar at the bottom right shows the Snipping Tool application is active.

# IBM Quantum Dashboard

The screenshot shows the 'Compute resources' tab of the IBM Quantum Platform. A blue callout box highlights the text: 'Here you can see all available Quantum Computers'. The page displays six resource cards:

- ibm\_brisbane**: System status: Online, Processor type: Eagle r3. Metrics: Qubits 127, EPLG 1.9%, CLOPS 5K.
- ibm\_osaka**: System status: Online, Processor type: Eagle r3. Metrics: Qubits 127, EPLG 2.8%, CLOPS 5K.
- ibm\_kyoto**: System status: Online, Processor type: Eagle r3. Metrics: Qubits 127, EPLG 3.6%, CLOPS 5K.
- simulator\_stabilizer**: Simulator status: Online, Simulator type: Clifford simulator. Metrics: Qubits 100.
- simulator\_mps**: Simulator status: Online, Simulator type: Matrix Product State. Metrics: Qubits 100.
- simulator\_extended\_stabilizer**: Simulator status: Online, Simulator type: Extended Clifford (e.g. Clifford+T). Metrics: Qubits 62.

Below the cards, there is a search bar and a link to 'Your systems & simulators (8)'. The URL in the address bar is https://quantum.ibm.com/services/resources?tab=yours.

# IBM Quantum Dashboard

The screenshot shows the IBM Quantum Platform dashboard with the Compute resources tab selected. The main panel displays details for the **ibm\_brisbane** system, which is online and has 127 qubits. A callout box highlights that by selecting a specific QPU, it's possible to see a number of details. Another callout box points to the 'Details' section, stating '127 qubits, only a subset of gates is supported'. A third callout box points to the 'Calibration data' section, stating 'Errors due to operations and measurements'.

By selecting a specific QPU, it is possible to see a number of details

ibm\_brisbane OpenQASM 3

**ibm\_brisbane**

System status: Online  
Processor type: Eagle r3

Qubits: 127 EPLG CLOPS 1.9% 5K

**simulator\_stabilizer**

Simulator status: Online  
Simulator type: Clifford simulator

Qubits: 5000

**ibmq\_qasm\_simulator**

Simulator status: Online  
Simulator type: General, context-aware

Qubits: 32

**ibm\_brisbane**

127 Qubits  
1.9% EPLG  
5K CLOPS

**Details**

Value	Description	Value	Description
127	Qubits	Status: Online	Median ECR error: 7.956e-3
1.9%	EPLG	Total pending jobs: 429 jobs	Median SX error: 2.449e-4
5K	CLOPS	Processor type: Eagle r3	Median readout error: 1.350e-2
		Version: 1.1.19	Median T1: 215.48 us
		Basis gates: ECR, ID, RZ, SX, X	Median T2: 135.03 us
		Your instance usage: 0 jobs	

**Instance access limits**

Your upcoming reservations: 0

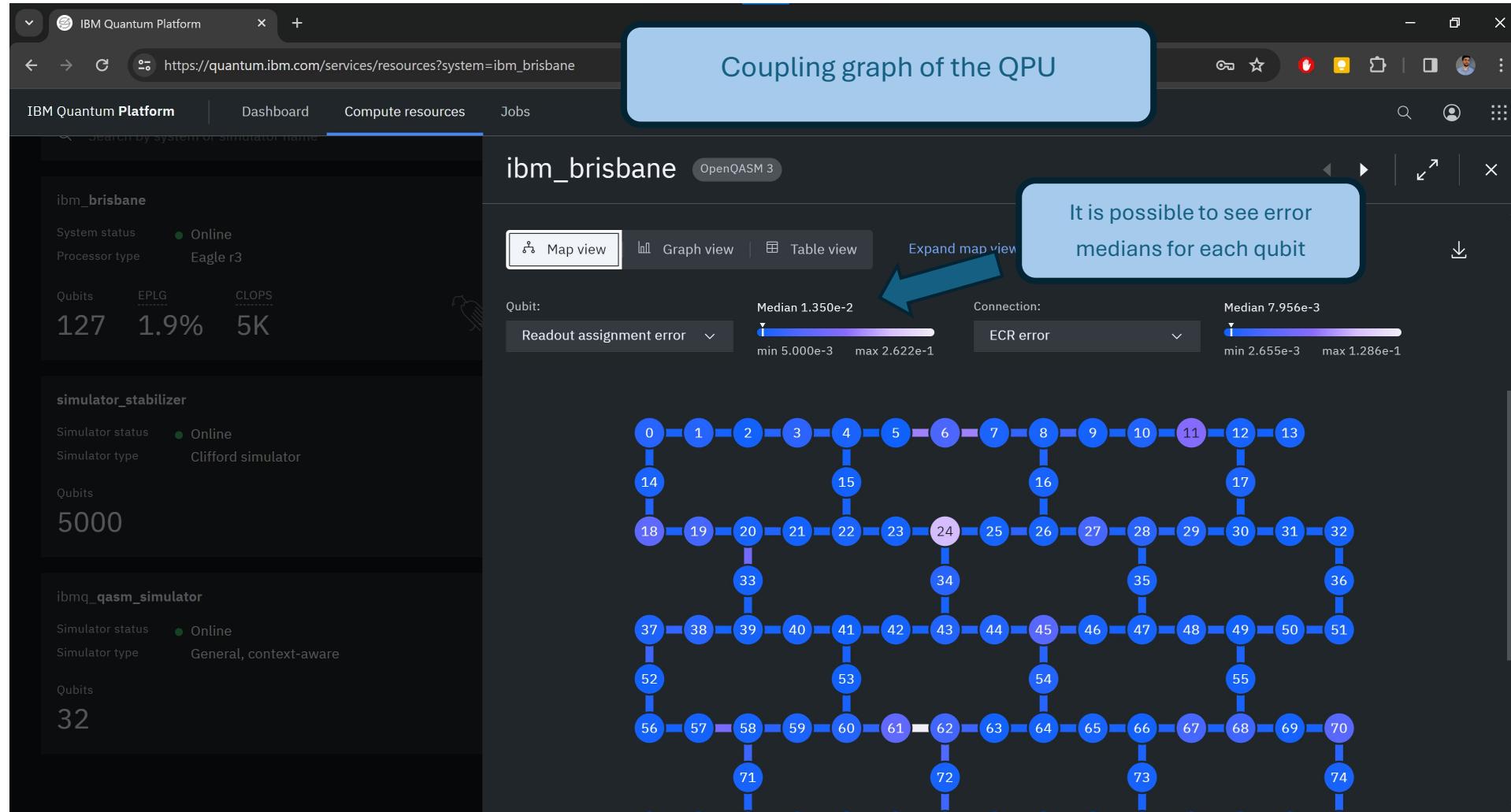
**Calibration data**

Last calibrated: about 1 hour ago

Map view Graph view Table view Expand map view

Qubit	Median Readout assignment error	Connection	Median ECR error
Readout assignment error	Median 1.350e-2 min 5.000e-3 max 2.622e-1	ECR error	Median 7.956e-3 min 2.655e-3 max 1.286e-1

# IBM Quantum Dashboard



# IBM Quantum Dashboard

The screenshot shows the 'Jobs' section of the IBM Quantum Platform. At the top, there's a header bar with tabs for 'IBM Quantum Platform', 'Dashboard', 'Compute resources', and 'Jobs'. The 'Jobs' tab is active, indicated by a blue underline. Below the header, a large callout box contains the text: 'Here you can find all your jobs' and 'Look for <>Workloads<> in the last version of the website'. Another callout box below it says: 'Every job represents a circuit you have run and its output'. The main area has a dark background with a light gray header. It includes a search bar labeled 'Search jobs by ID, name or tag' and a dropdown menu 'All statuses'. A table header with columns: 'Job Id' (with a checkbox icon), 'Session Id', 'Status', 'Created' (with a downward arrow), 'Completed', 'Program', 'Compute resource', 'Usage', and 'Tags'. Below the table, there's a message: 'You do not currently have any jobs' with a small cube icon, followed by a explanatory text: 'Once you have run a circuit on a system or simulator, you can track the job's status and view details from this table.'

# IBM Quantum Dashboard

The screenshot shows the 'Jobs' page of the IBM Quantum Platform. At the top, a blue callout box contains the text: "For example, if you are sending a circuit to the QPU, you will find it here...". The main area displays a table of jobs. The table has columns for Job Id, Session Id, Status, Created, Completed, Program, Compute resource, Usage, and Tags. One job is listed:

Job Id	Session Id	Status	Created	Completed	Program	Compute resource	Usage	Tags
cqyrjk2s9z7g00...		Queued Est. wait: 2 hours	22 minutes ago		sampler	ibm_osaka Queue position: 18	Est. 31.1s	

At the bottom of the table, it says "Items per page: 10" and "1-1 of 1 items". The footer of the page includes links for Terms, Privacy, Cookie preferences, and Support, along with icons for brightness, monitor, and refresh.

# IBM Quantum Dashboard

The screenshot shows a browser window for the IBM Quantum Platform. The URL is <https://quantum.ibm.com/jobs/cr0mxf5jjt100088eb2g>. The navigation bar includes links for IBM Quantum Platform, Dashboard, Compute resources, and Jobs. The Jobs section is active.

The main content area displays a job summary for a completed task:

Details	
Total completion time	21m 32.3s
Compute resource	ibm_osaka
Status:	Completed
Instance:	ibm-q/open/main
Program:	sampler
# of shots:	100
# of circuits:	1

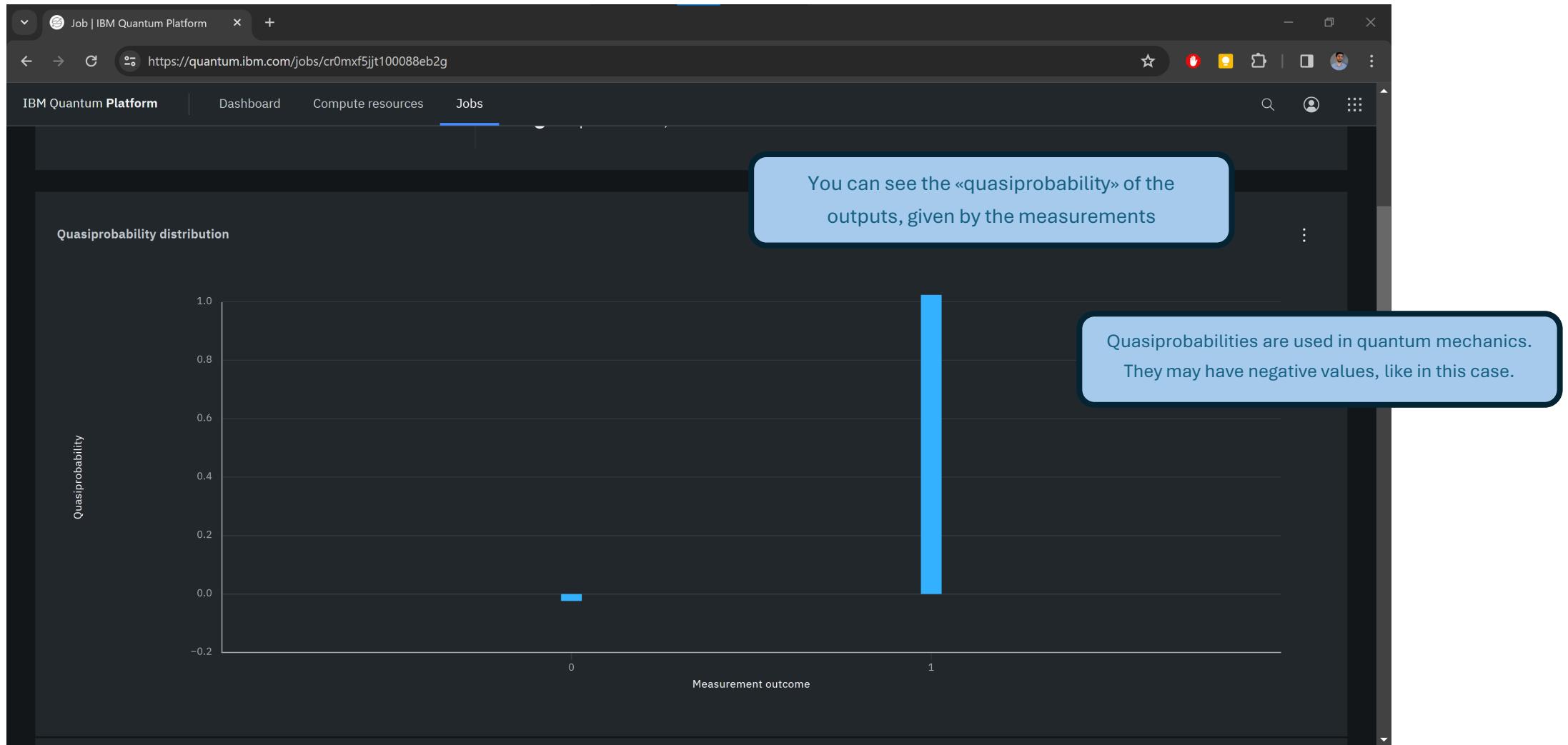
A status timeline on the right lists the following events:

- Created: Mar 25, 2024 11:15 AM
- In queue: 4m 23.1s
- Running: Mar 25, 2024 11:19 AM  
Qiskit runtime usage: 16s
- Completed: Mar 25, 2024 11:36 AM

A callout box highlights the timeline information with the text: "Once the job has finished, you can find details about the task".

Below the details, there is a section titled "Quasiprobability distribution" which contains a plot showing a single sharp peak at approximately 1.0 probability.

# IBM Quantum Dashboard



# IBM Quantum Dashboard

The screenshot shows the IBM Quantum Platform interface with the 'Jobs' tab selected. The main area displays a quantum circuit editor. On the left, under 'Circuit', there are two tabs: 'Qasm' (selected) and 'Qiskit'. Below these tabs, the 'Original circuit' section contains 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;
```

To the right, the 'Transpiled circuit' section shows the generated 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
```

A callout bubble points to the 'Qasm' tab with the text: 'For every job, you can also see the circuit representation in QASM, which is Quantum Assembly (a common standard).'. At the bottom center, there is a link labeled '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.  $\omega_N^{nk}$  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:

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

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:

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

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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