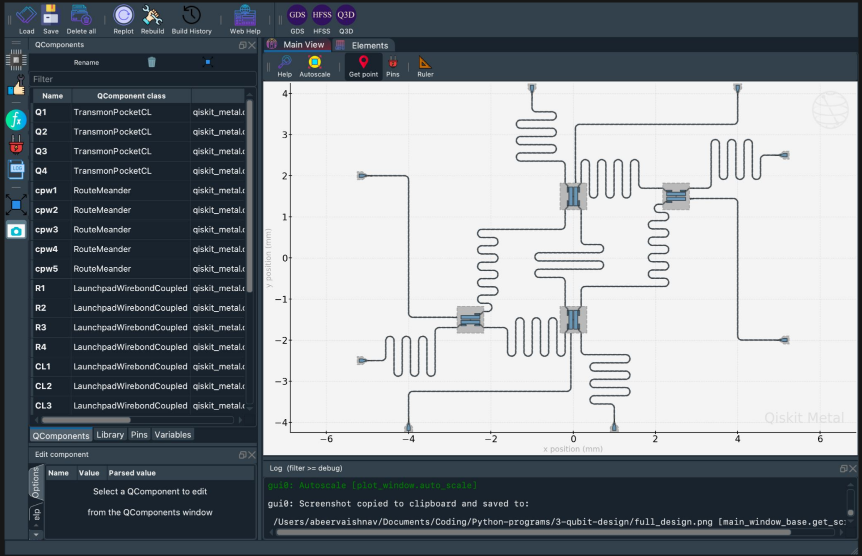
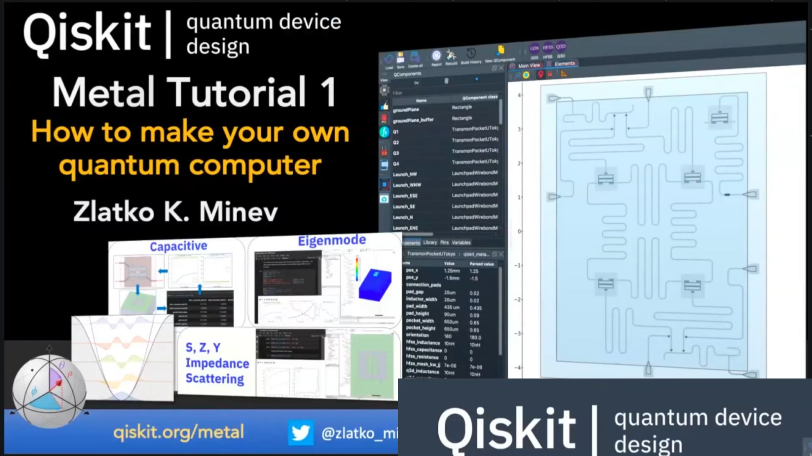
Designing a 4-qubit Superconducting Chip from Scratch

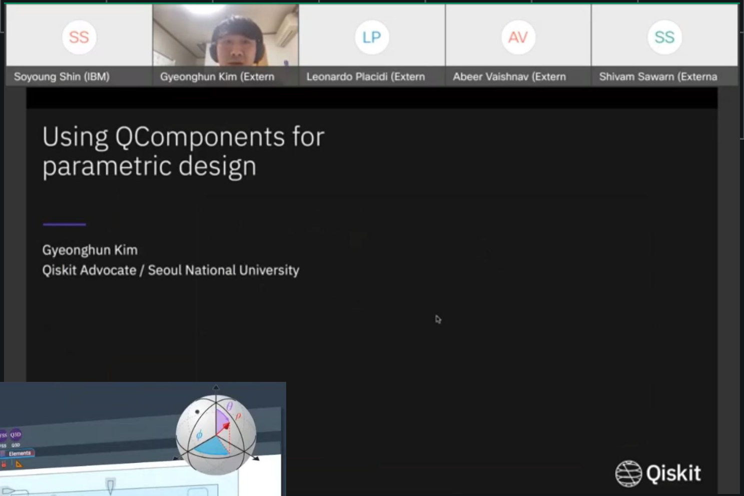


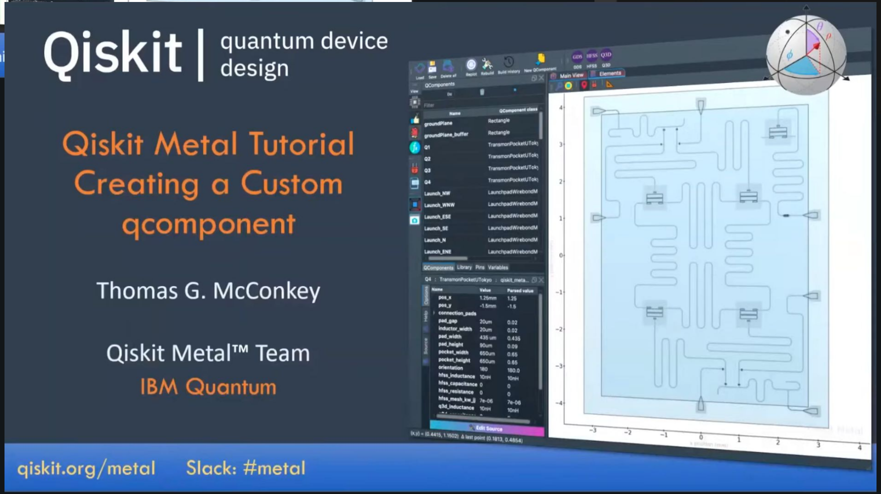
A bit about myself …

- Qiskit Advocate (2021 - Present)
- Duke University (MS, Electrical and Computer Engineering -- Quantum Hardware)
- Present Research: Superconducting and Trapped-ion hardware design and simulation
- Past Research: Quantum algorithms and circuit optimization for Near-term quantum computers
- Using Qiskit Metal for about 1 year
- IBM Quantum Intern - Summer 2022 (focusing on Qiskit Metal)

Our journey until now

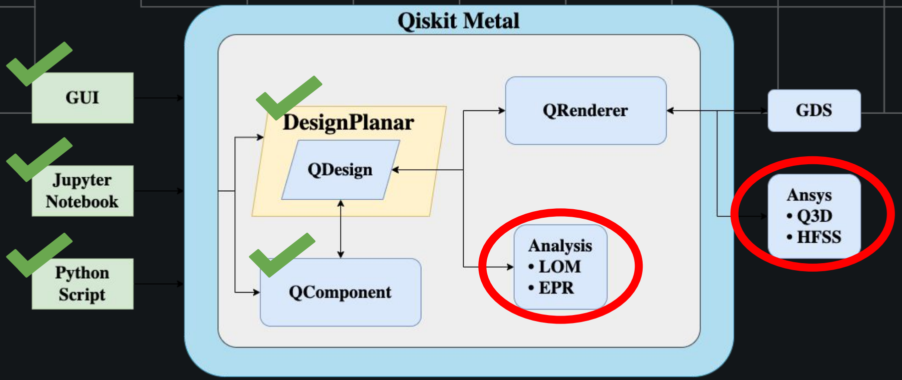






Our journey until now

- Qiskit Metal
  - What?
  - Why?
  - How?
- Placing components in the Metal GUI
- Making the chip layout
- Making custom QComponents for flexibility and reproducibility



How do we make sure that our design works as expected?

This is how... Analyses

Lumped Capacitive

Quasi Lumped

Energy Participation Ratio

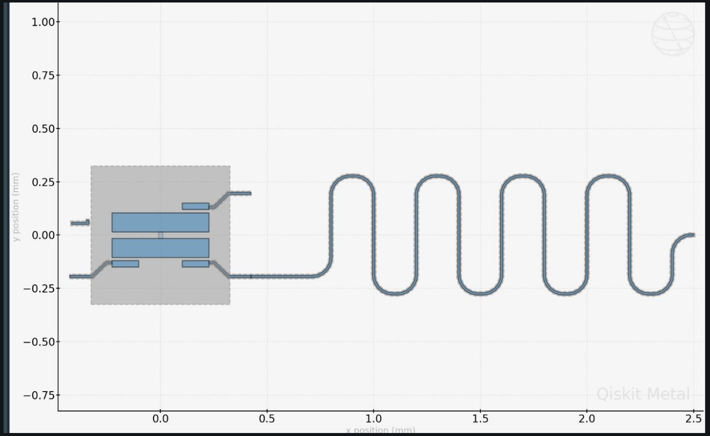
*Old LOM

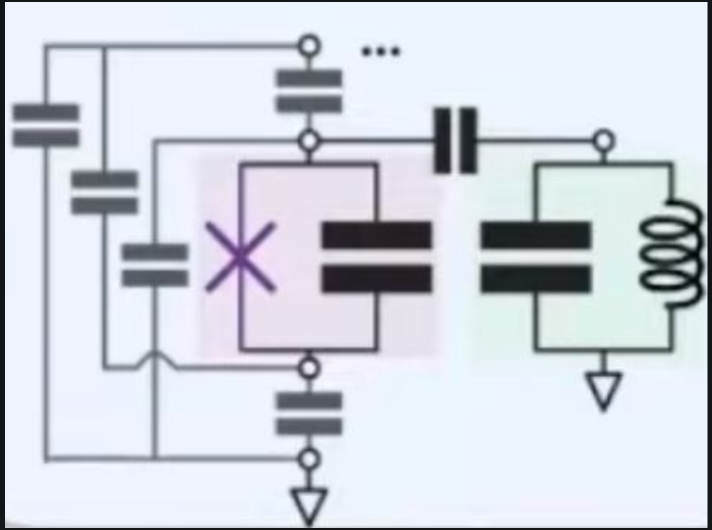
*New LOM

NOTE: Impedance or Black-Box Quantization Analysis is not covered in this lecture, but that is also another option available for analysis in Qiskit Metal.

Lumped Capacitive Analysis

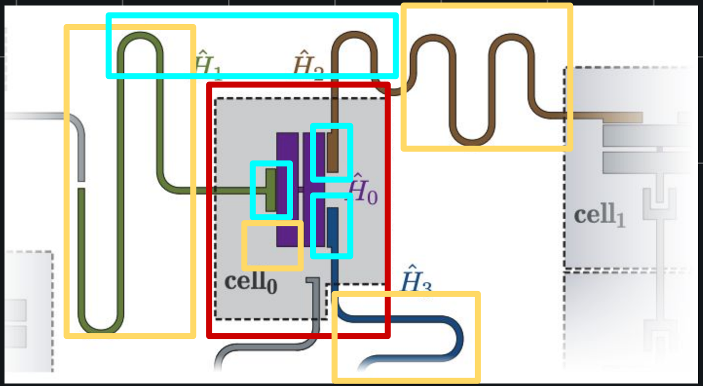
Lumped Capacitive analysis method is the most computationally efficient method which makes an assumption of components being in the “lumped” regime and models the connections as as **point capacitors** and **inductors**.





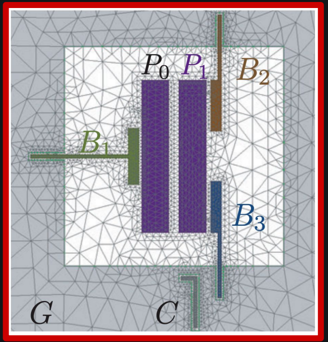
** Not very reliable, may have ~20% error compared to fabricated device.

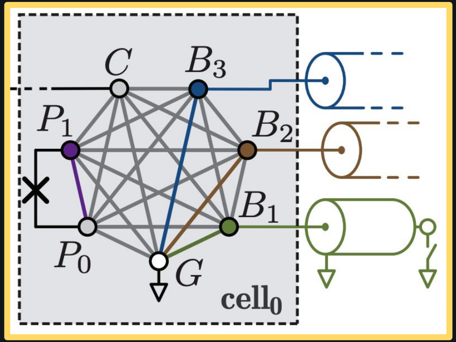
Quasi-Lumped Analysis[4]

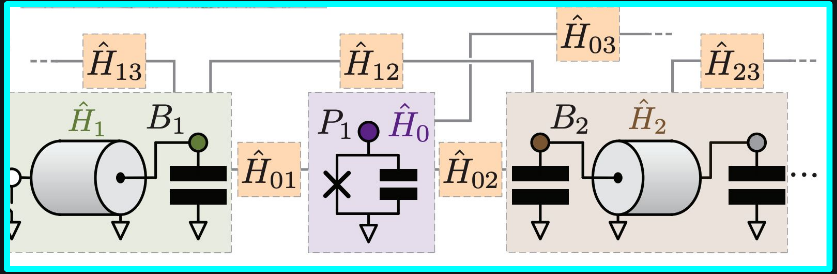


Quasi-Lumped analysis method is a computationally efficient process to solve for the Hamiltonian of an interacting quantum information processing system.

It partitions the composite system into **compact lumped** or **quasi-distributed cells**.







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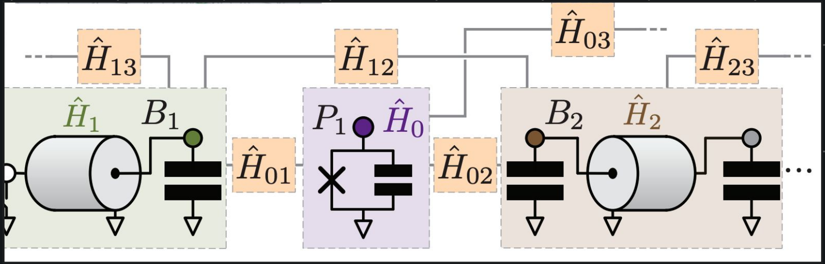
[4] Z. K. Minev et al.: **arXiv:2103.10344**

Quasi-Lumped Analysis[4] - Steps

$$H_{full} = \hat{H}_0 + \sum_{n=1}^{K} \hat{H}_n + \sum_{n=0}^{K-1} \sum_{m=n+1}^{K} \hat{H}_{nm}$$

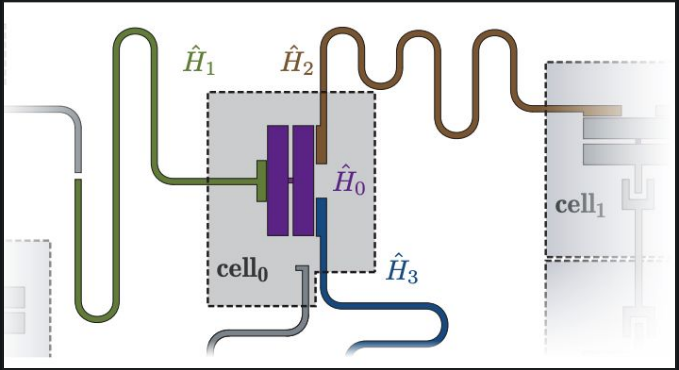


1. The qubit cell is taken and simulated in **Ansys Q3D Solver**. The output is a **capacitance matrix** between each component.

2. Capacitance matrix is used to solve for:
   a. $E_J = \hbar I_c / 2e$
   b. $E_c = e^2/2C$
   c. Transmon energy levels (by diagonalizing the H)

3. Qubit-bus and bus-bus couplings are then calculated

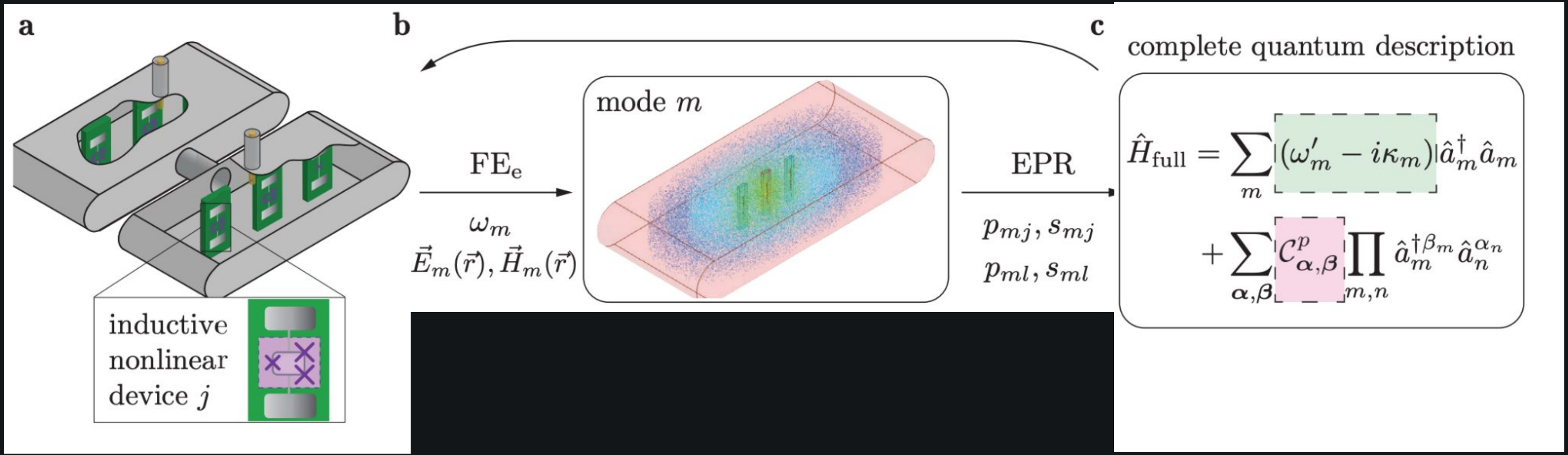
4. Finally, we assume Q-factors and calculate T_1 value.



[4]Z. K. Minev et al.: **arXiv:2103.10344**

EPR Analysis[3]

Energy Participation Ratio analysis tries to answer a very simple question:
"What fraction of energy of mode **'m'** is stored in element **'j'** ?"



[3]Z. K. Minev et al.: **arXiv:2010.00620**

EPR Analysis[3] - Steps

$$\hat{H}_{full} = \hat{H}_{lin} + \hat{H}_{nl}$$

$$\hat{H}_{lin} = \hbar\omega_c \hat{a}_c^\dagger \hat{a}_c + \hbar\omega_q \hat{a}_q^\dagger \hat{a}_q$$

$$\hat{H}_{nl} = -E_J[\cos(\hat{\varphi}_J) + \hat{\varphi}_J^2/2]$$

$$\hat{\varphi}_J = \varphi_q(\hat{a}_q + \hat{a}_q^\dagger) + \varphi_c(\hat{a}_c + \hat{a}_c^\dagger)$$

$$\varphi_c^2 = p_c \frac{\hbar\omega_c}{2E_J} \quad \text{and} \quad \varphi_q^2 = p_q \frac{\hbar\omega_q}{2E_J}$$

$$p_m = \frac{\text{inductive energy stored in the junction}}{\text{total inductive energy stored in mode } m}$$

Aim: To determine the non-linear part of H_{full} and reconstruct H_{full}.

1. Calculate quantum zero-point fluctuations using the participation of junction in the eigenfield solution.
2. Participation ratio for mode ***'m'*** is given by $\mathbf{p_m}$. This is used to calculate the junction flux.
3. Now, we can reconstruct the full Hamiltonian and get the eigenstate energies (and frequencies), anharmonicities, and cross-Kerr couplings for the whole system.

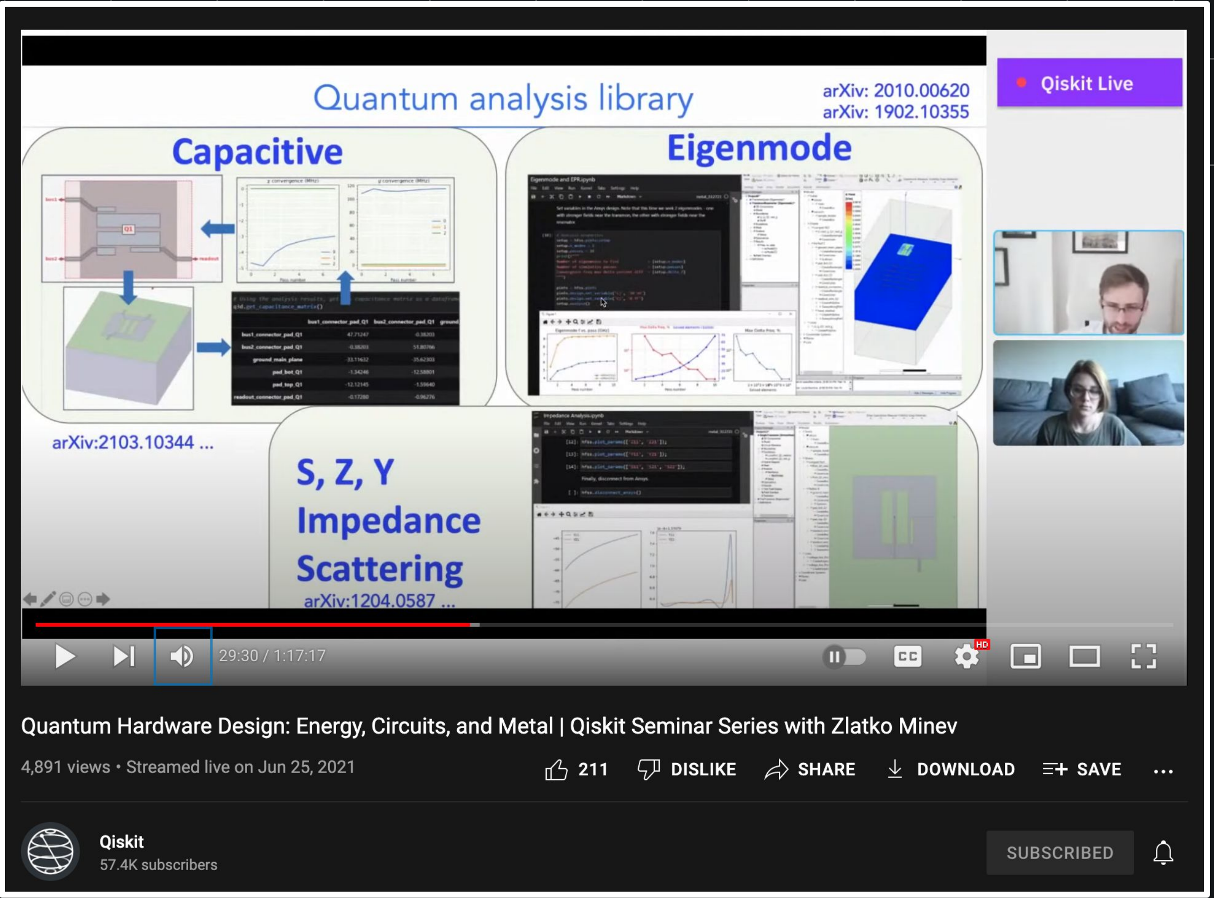
[3] Z. K. Minev et al.: **arXiv:2010.00620**

For a more in-depth overview …

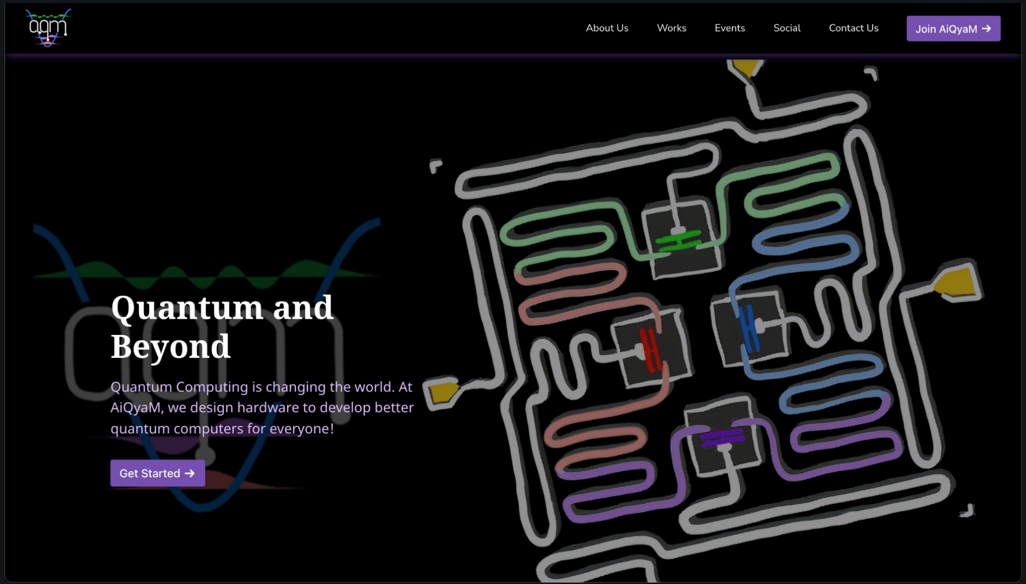
EPR:
https://www.youtube.com/watch?v=jjdYHZ0qxcY

https://www.youtube.com/watch?v=ITCkKfjxcbc&list=PLOFEBzvs-VvqHl5ZqVmhB_FcSqmLufsjb&index=8

Quasi-Lumped:
https://www.youtube.com/watch?v=S8Wx2Lo2CxQ&list=PLOFEBzvs-VvqHl5ZqVmhB_FcSqmLufsjb&index=22



Thank You!



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