WELCOME TO TUTORIAL

Janus 2.0: Background of Quantum Computing

https://janusq.github.io/tutorials/

College of Computer Science and Technology,
Zhejiang University

ASPLOS 2024

Outline of Presentation

- **Background and challenges**
- QuCT overview
- Upstream model: Circuit feature extraction
- Downstream model 1: Circuit fidelity prediction
- Downstream model 2: Unitary decomposition
- Experiment

Background Knowledge

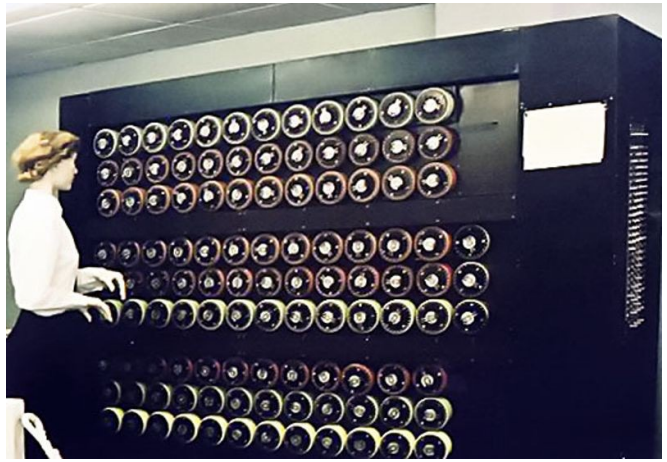
Development of Classical Computing

Motivation of Quantum Computing

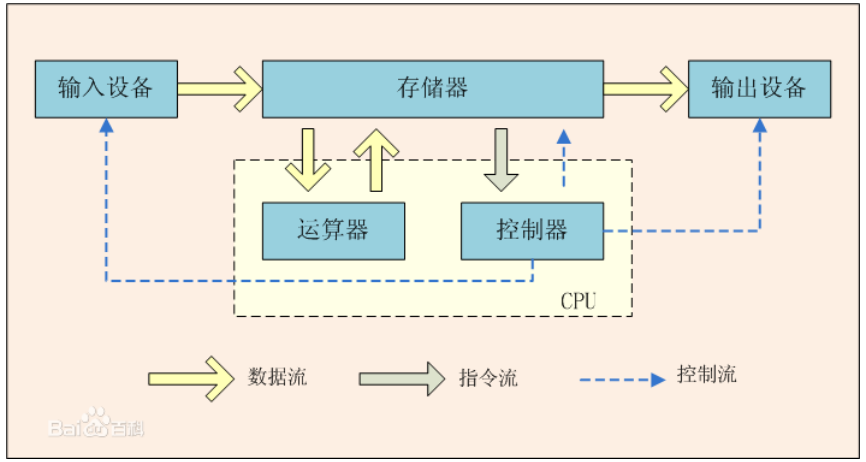
Development of Quantum Computing

Development Of Classical Computing

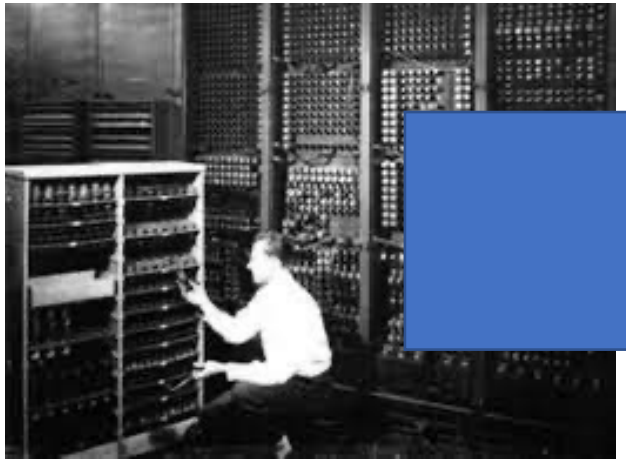
专用机（1939）



冯诺依曼 结构（1947）

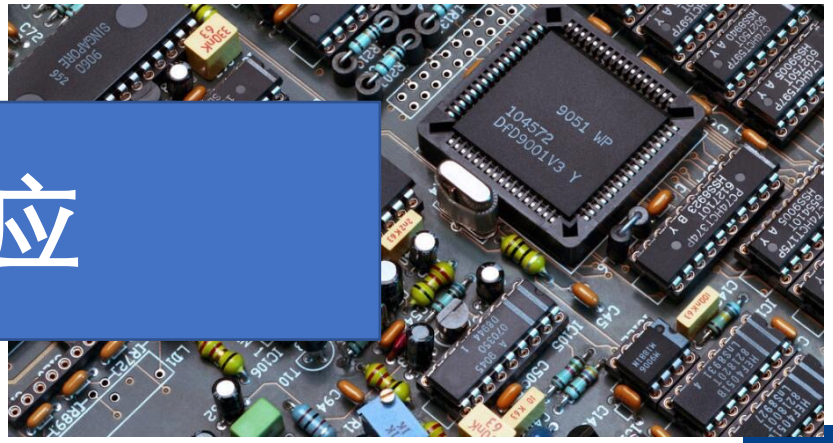


真空管计算机 ENIAC（1942）



晶体管计算机TRADIC（1954）

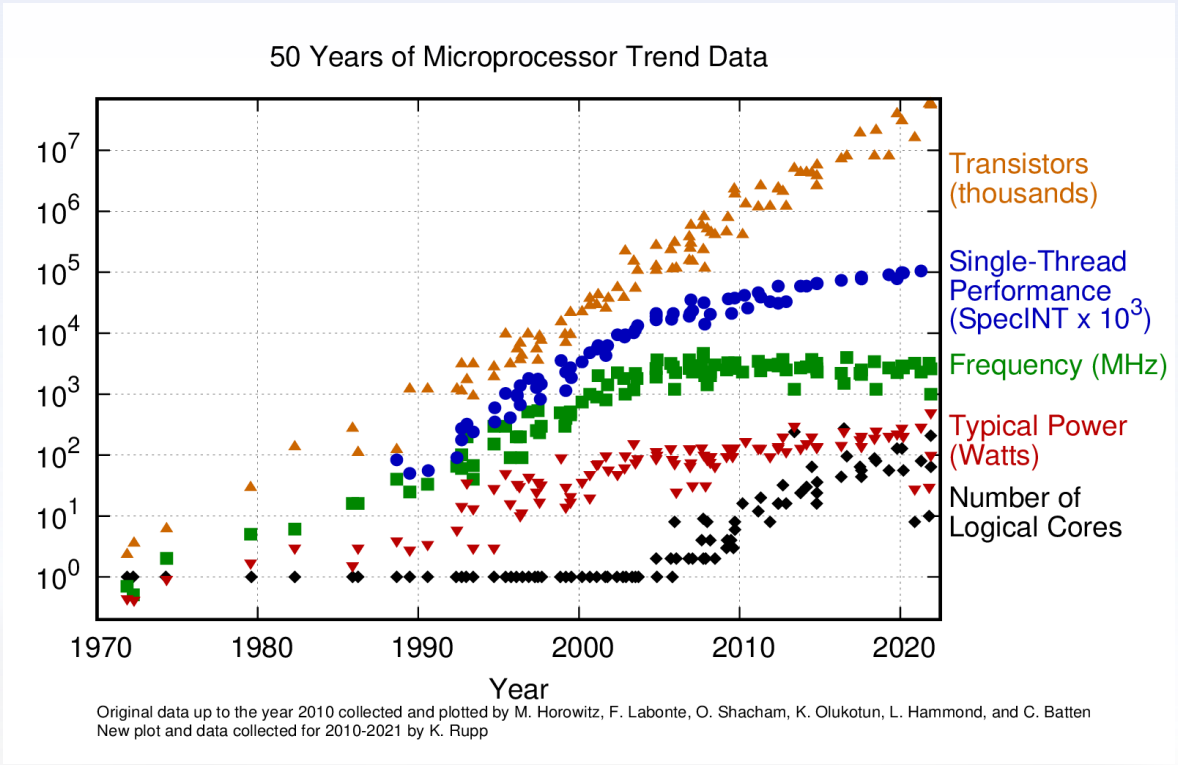
大规模、超大规模集成电路



量子力学的宏观效应

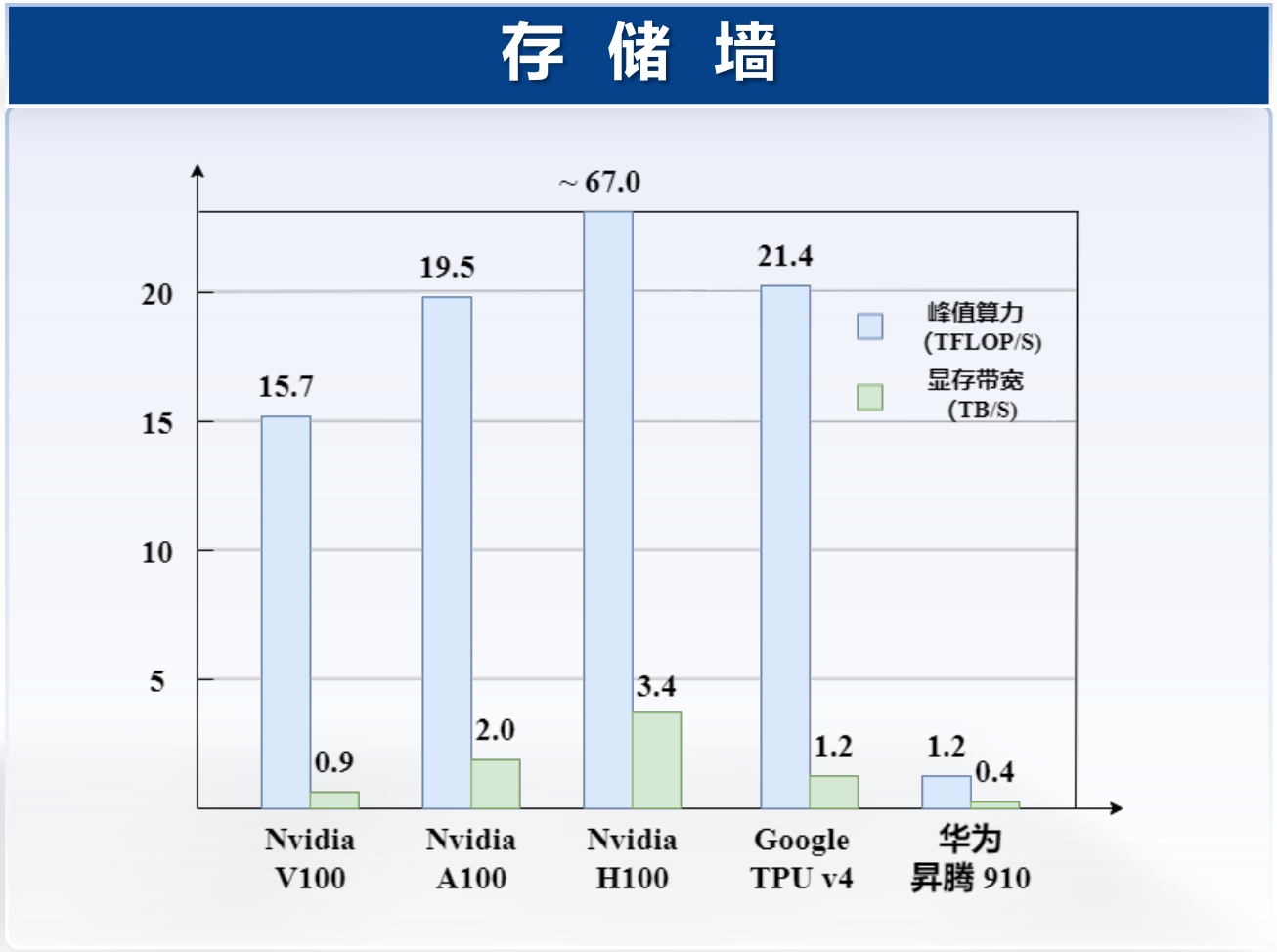
Motivation Of Quantum Computing

计 算 墙



- 先进芯片制程的研发成本与研发周期不断增长，**摩尔定律接近失效**，单位面积芯片的计算能力提升有限。
- 计算系统的发展无法依赖传统单一芯片的发展，需要**颠覆性的芯片设计方法、新型计算原理**绕过芯片制程限制。

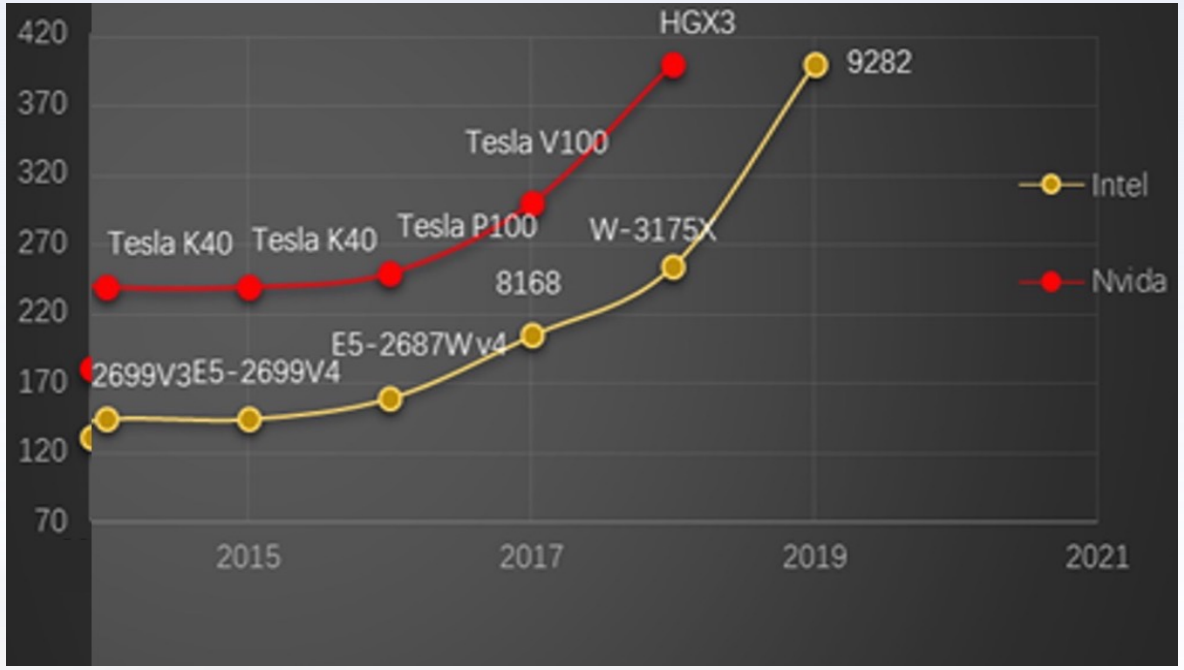
Motivation Of Quantum Computing



- 算力与带宽发展严重不匹配，**系统存储与带宽成为发展瓶颈**，访存时延高、效率低，CPU 性能发挥受到限制。
- 计算系统的设计需要考虑**存算一体化**，提高**数据与算力的协同效率**，需要特别研究非冯架构的芯片互联。

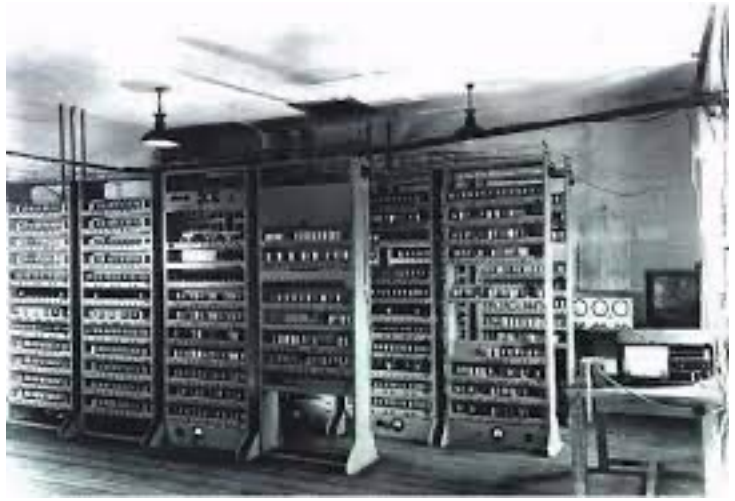
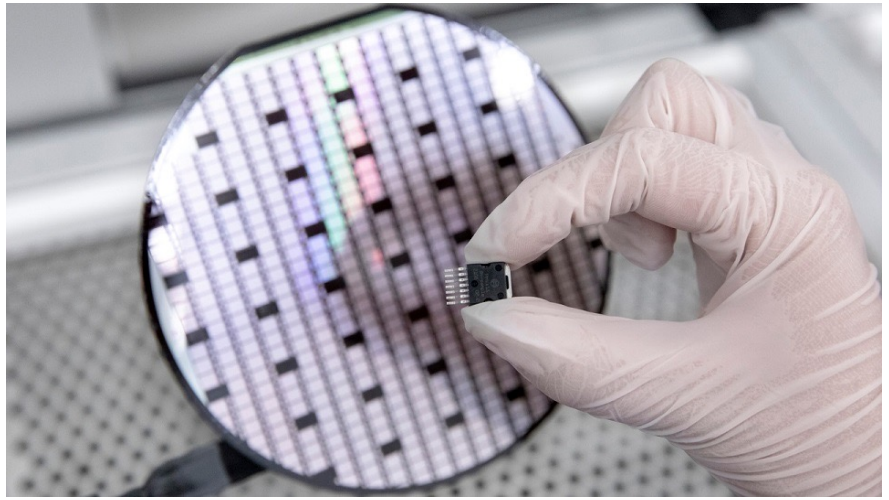
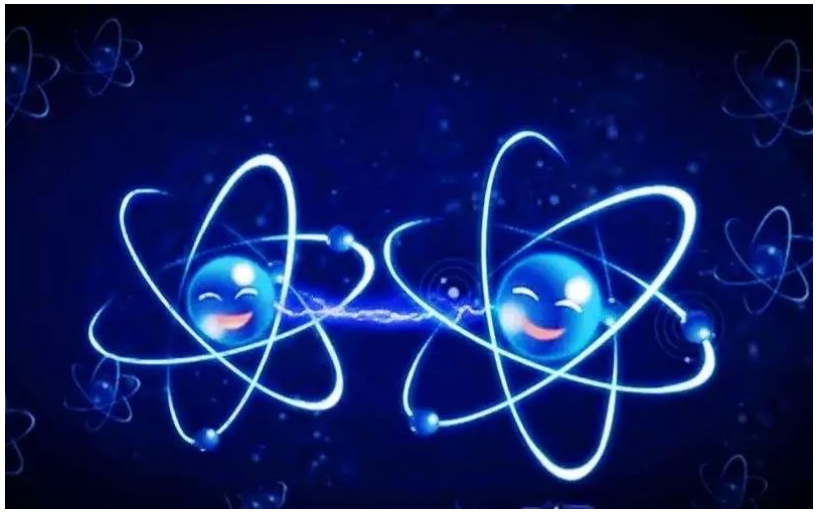
Motivation Of Quantum Computing

功 耗 墙

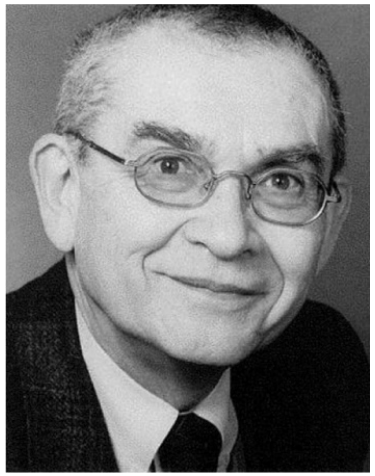


- 通用芯片与智能芯片的**功耗随算力发展指数级上升**，能源消耗的成本环保问题已成为制约算力发展主要因素。
- 计算系统的优化将**从架构层面考虑系统资源调度**，在相同功耗的前提下，提高算力资源的利用效率。

Proposal of Quantum Computing

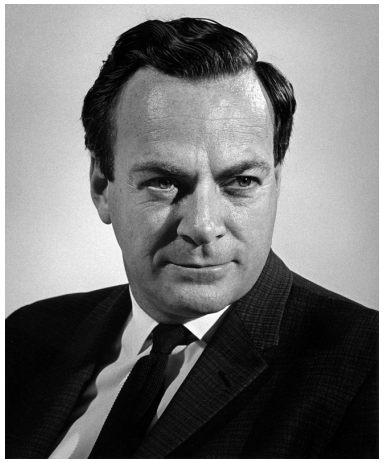




- 计算机技术使设备越来越小，经典物理学不再是物理定律的合适模型。



Yuri Manin

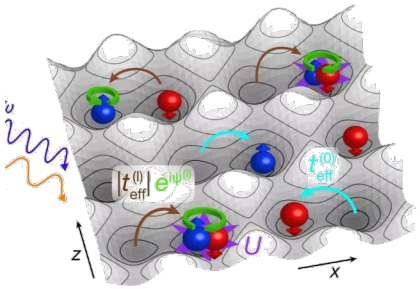
- 代数几何
- 丢番图几何
- 曼宁(1980年)与费曼(1981年)最早提出量子计算机想法。



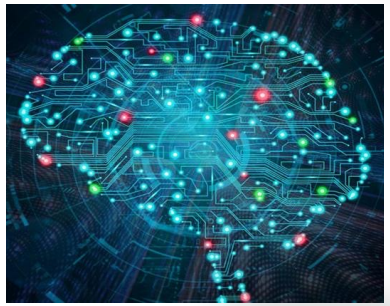
Richard Feynman

- 费曼路径积分，费曼图，费曼部分子模型
- 量子电动力学，诺贝尔物理学奖
- 1982年，费曼提出：
- 用经典计算机模拟量子过程需要指数级资源，而量子计算机则可以有效地模拟量子过程。

Basic Concepts of Quantum Computing



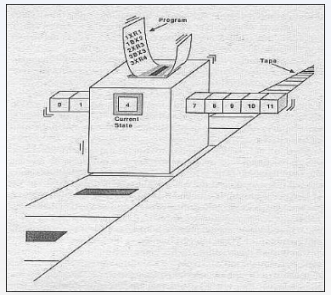
Physical Simulation

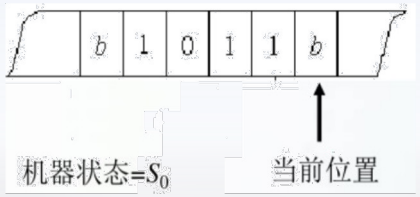


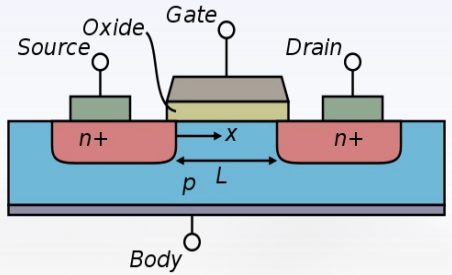
Factor

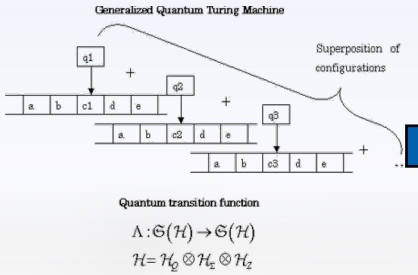
Application

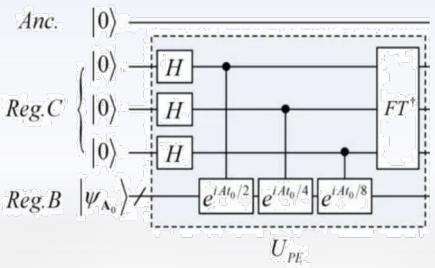
	Computing theory	Encoding	Physical implementation
经典程序	Classical Turing machine	Program based on binary encoding	CMOS (0/1)
量子程序	Quantum Turing machine	Circuit-based quantum program	Superconducting, photon (superposition state)

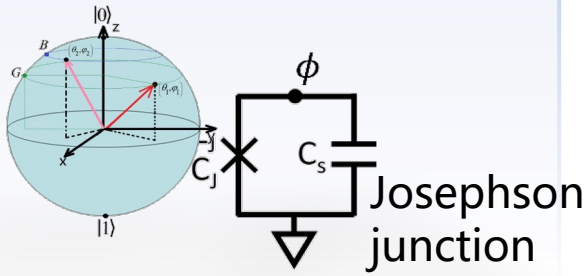












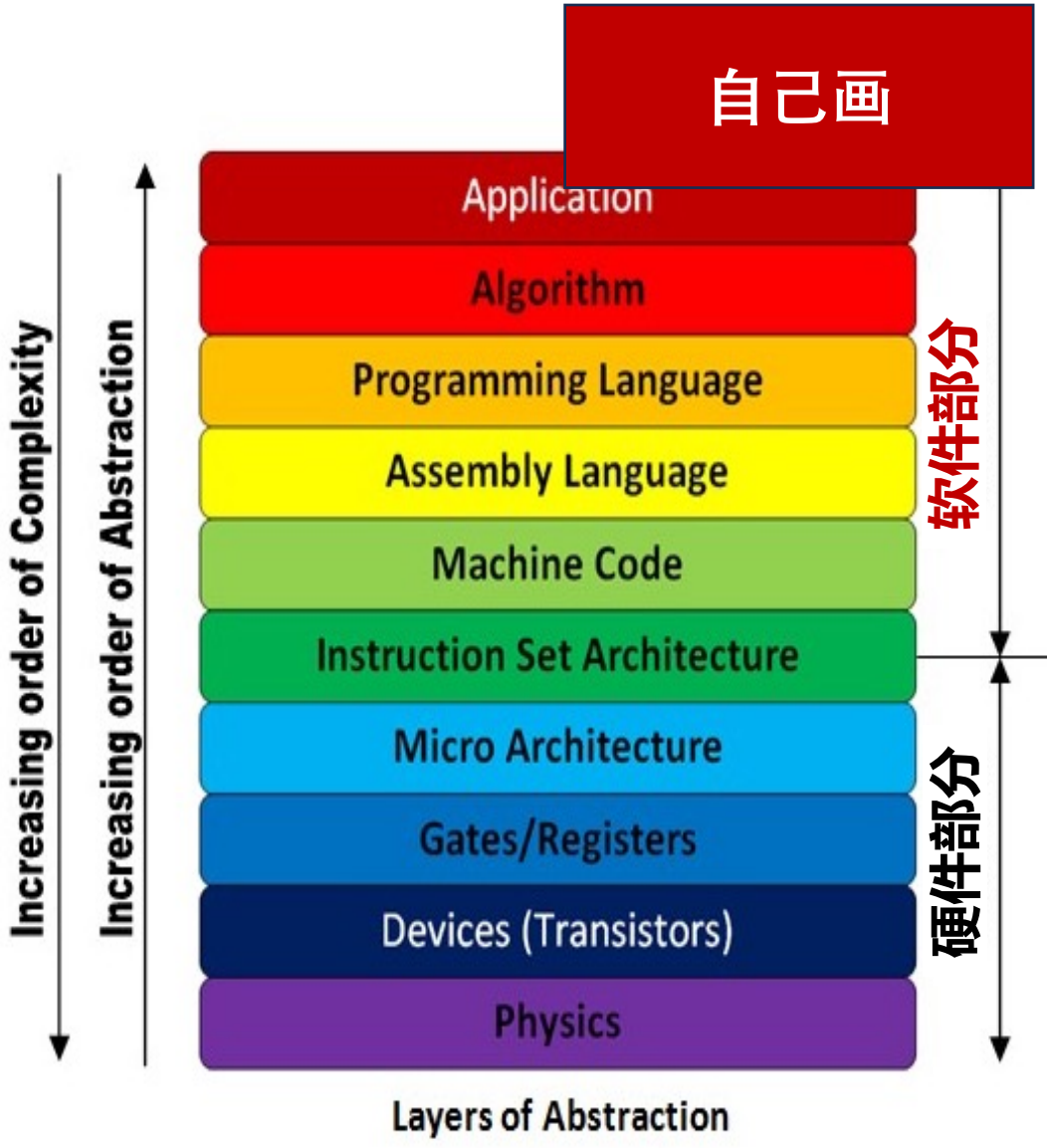
通过并行带来计算能力的优势

因为量子坍缩、叠加性质导致语言的复杂性

由于可逆和超导性带来能耗的巨大提升

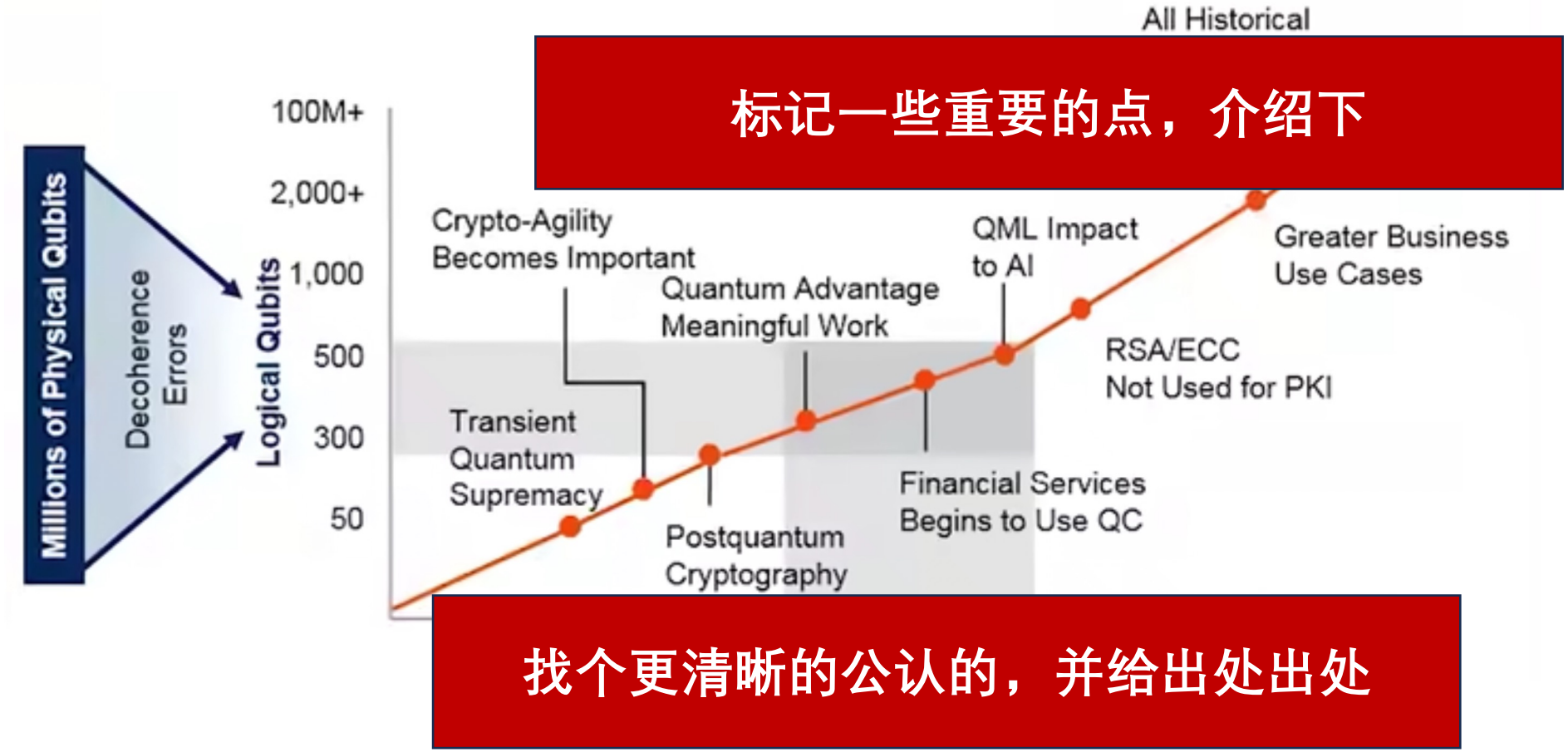
经典程序 对比 量子程序

Quantum Computing Architecture



	经典体系结构	量子体系结构
应用	LLM Model	SAT问题
算法	矩阵乘法	二次项优化算法
编程语言	Python	Python
汇编语言	ADD/MUL	量子电路描述
机器语言	0011011	cos, sin波函数
指令集	x86	波形控制指令
微体系结构	i7处理器	量子芯片架构
逻辑结构	与非门、或门	量子态、量子门
设备	CMOS晶体管	超导量子、光量子
物理原理	半导体物理	量子力学

Development of Quantum Computing



Mathematical Model of Quantum Computing

Qubits

Quantum Evolution

Quantum Circuit

Quantum Bit (Qubit)

Single qubit

A **qubit** has two bases $|0\rangle$ and $|1\rangle$. The information stored in its **superposition state** is represented as a **2-dimension state vector** $|\varphi\rangle$.

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$$

$$|1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\varphi\rangle = \begin{bmatrix}\alpha\\\beta\end{bmatrix}$$

subject to $|\alpha|^2 + |\beta|^2 = 1$

Multiple qubits

***N* qubits** has 2^N bases $|00\cdots0\rangle$, $|00\cdots1\rangle\cdots$, $|11\cdots1\rangle$. The information stored in their **superposition state** is represented as a 2^N**-dimension state vector**.

$$|00\cdots0\rangle = \begin{bmatrix}1\\0\\\vdots\\0\end{bmatrix} \quad |00\cdots1\rangle = \begin{bmatrix}0\\1\\\vdots\\0\end{bmatrix} \quad \cdots \quad |11\cdots1\rangle = \begin{bmatrix}0\\0\\\vdots\\1\end{bmatrix}$$

$$|\varphi\rangle = \alpha_0|00\cdots0\rangle + \alpha_1|00\cdots1\rangle + \cdots + \alpha_{2^N}|11\cdots1\rangle$$

$$|\varphi\rangle = \begin{bmatrix}\alpha_0\\\alpha_1\\\vdots\\\alpha_{2^N}\end{bmatrix}$$

subject to $|\alpha_0|^2 + |\alpha_1|^2 + \cdots |\alpha_{2^N}|^2 = 1$

Quantum Evolution

Unitary matrix

A quantum evolution caused by **quantum gates** is represented as a **unitary matrix (unitary),** which is a square matrix whose conjugate transpose is its inverse.

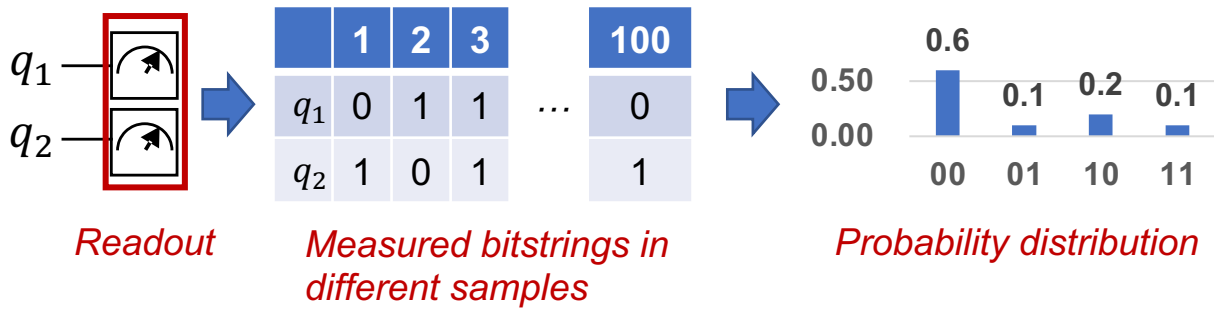
$$UU^{\dagger} = I$$

The evolution of qubit state $|\varphi\rangle$ is represented as:

$$|\varphi'\rangle = U|\varphi\rangle$$

Quantum readout

A sampling of a quantum state is a bitstring. Multiple sampling of this state composes a probability distribution of measuring different bitstrings.



Readout

Measured bitstrings in different samples

Probability distribution

给个单比特旋转的例子

给个单比特探索的例子，比如一个位置有40%到0, 60%到1

Quantum Circuit

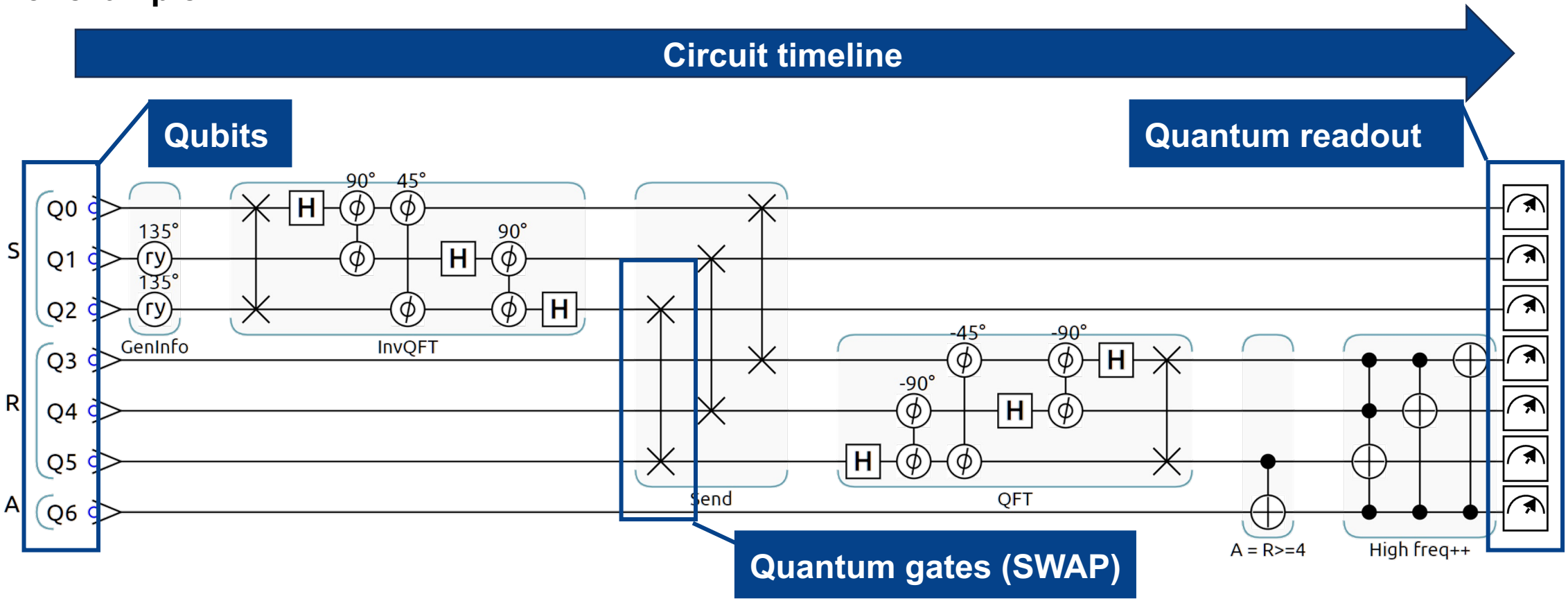
ZHEJIANG UNIVERSITY

Quantum gates

Qubit timeline

Quantum Circuit

For example



给个部分电路的酉矩阵计算的例子

Implementation of Quantum Circuit

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On superconducting quantum computer

Step 1. Circuit statement

Step 2. Circuit compilation

整个漫画一步一步怎么跑程序的

Step 3. Circuit execution

Step 4. Result post-processing

Overview of JanusQ 2.0

Motivation

Architecture

Getting start

Challenge in Quantum Computing

后面再展开讲

Noise **Instructions** **Topology** **Scalability**

Constrained by physical implementation

Motivation

1. 硬件少
2. 编译难 （慢，不精准，软硬件co-design）
3. 硬件校准难
4. 有加速的例子少

Installing JanusQ

Available platforms: Linux, Mac, Windows

Hardware requirements：

- Classical computer: > xx CPU， > xx GB Memory
- Quantum computer: > xx qubit, Superconducting QC is preferable.

给个大拇指符号

Simulator

Two methods

- From Wheels

下载地址

命令

- From Docker

下载地址

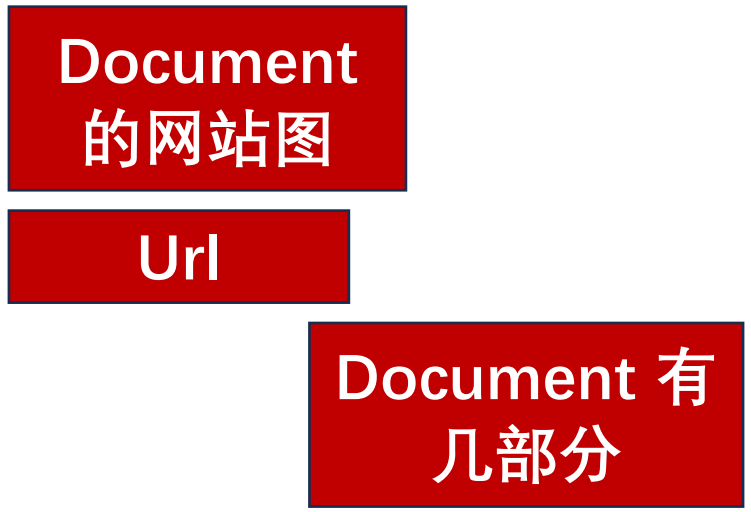
命令

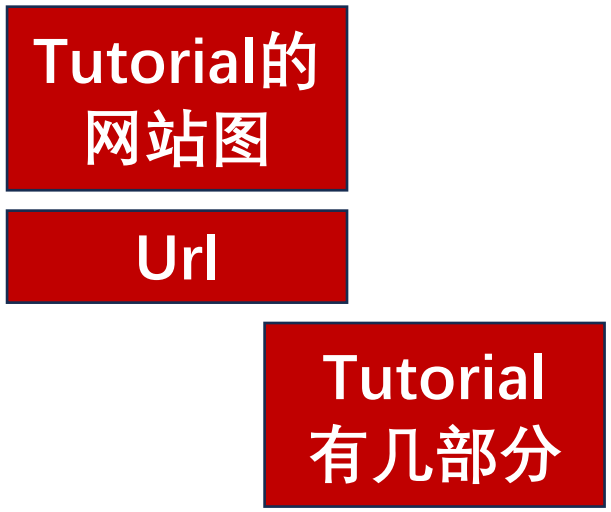
Docker的安装教程

Testing the installation

确认是否装成功了

Document and Example





Containing all the examples running in the tutorial