ACML 우주항공 연구 소개 및 양자 컴퓨팅 기반 유동 해석

Introduction to ACML Aerospace Research and Fluid Flow Analysis Based on Quantum Computing

명 노 신

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Aerospace Computational Modeling Laboratory (ACML)

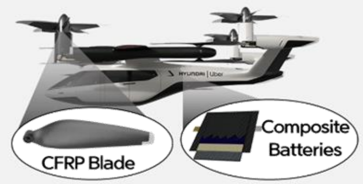
http://acml.gnu.ac.kr/

June 2nd, 2025 (16:00-17:20)

Mechanical and Robotics Engineering Seminar, GIST, Gwangju

ERC: 미래형 항공기 기체구조 및 안전 핵심기술

Aircraft Quality, Automotive Quantity
미래형 항공기 특성



열가소성 복합재 적용 필수

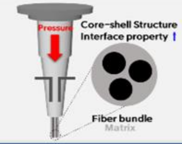
비행체 대량생산 요구

다수기체 운용, 짧은 운용주기

미래항공산업의 대응을 위한
일체형/안전 · 다기능 복합재료 혁신

일체형 대형 복합재

Core-shell 복합재 필라멘트



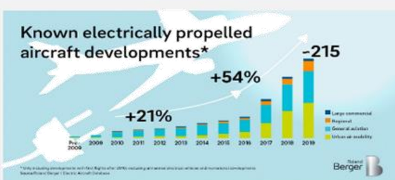
선도그룹 미국 ORNL와의 차별화

Hybrid 잔류수명 평가 기술

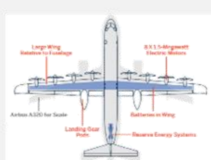
미래 항공기 복합재 구조

Hybrid 기반 고속 잔류수명 평가 기술

탄소중립 달성을 위한 친환경
전기추진 항공기 수요 대응 필요



전기추진 항공기 시장 수요 급증



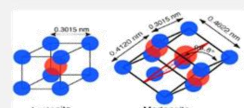
전기추진 항공기 비행 사례 (22년 9월)

90인승 800km

미래형 항공기 적용을 위한
저비용, 고신뢰도 안전 핵심기술

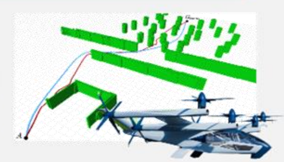
형상기억합금

초수성 코팅 방제빙



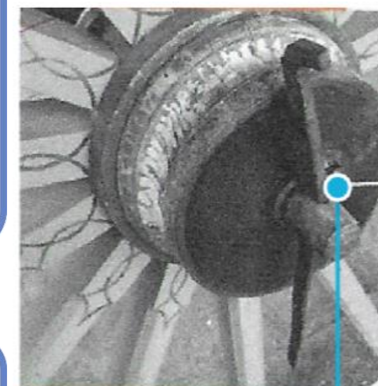
선도그룹 캐나다 McGill 대학과의 차별화

결빙풍동시험



성능검증 시험평가

고신뢰도 제어기술

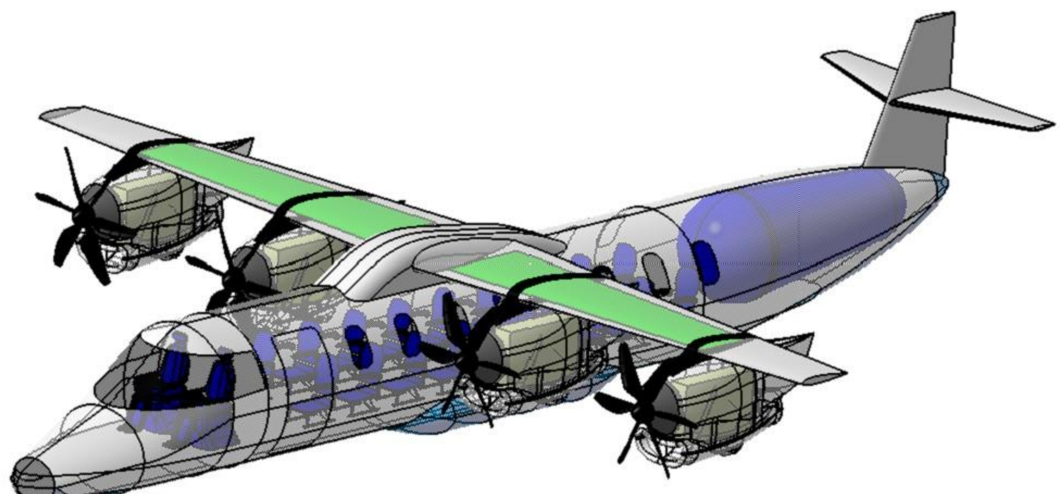


린치핀

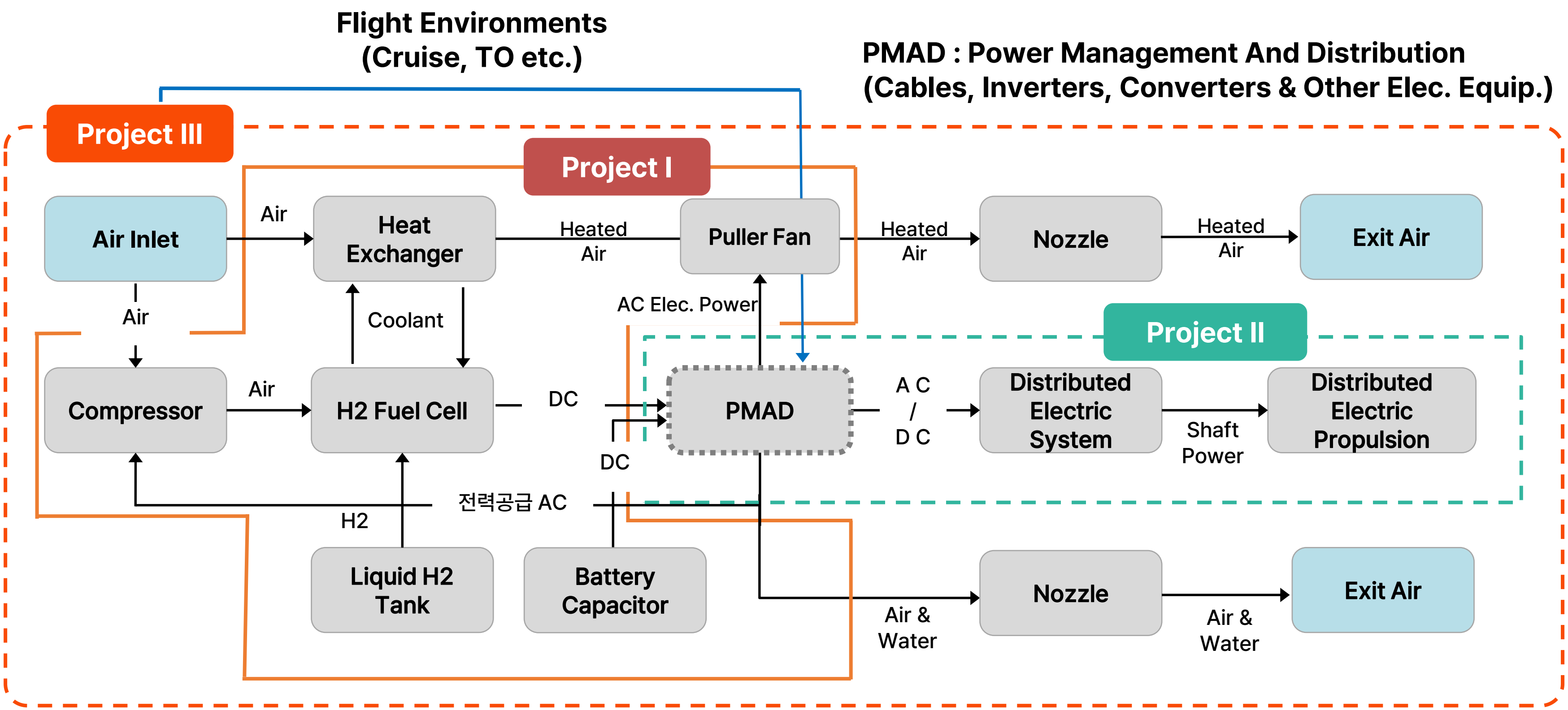
Linchpin Technology

Hydrogen Commuter Mega Project Led by GNU

Project Title	Technology for commuter-class aircraft using hydrogen-fuel-cell-powered hybrid distributed electric propulsion
Participating Organizations	10 including **GNU (Leading)**, UNIST, KERI, **KAI, Hanwha Aerospace Co.** 2 Local Government: Gyeongnam & Ulsan
Budget	**6.42 Million USD (On-going 1 Phase; 2023-25)** (Planned 2-3 Phase; 2026-2032)



Core Technology for Hydrogen Commuter Project



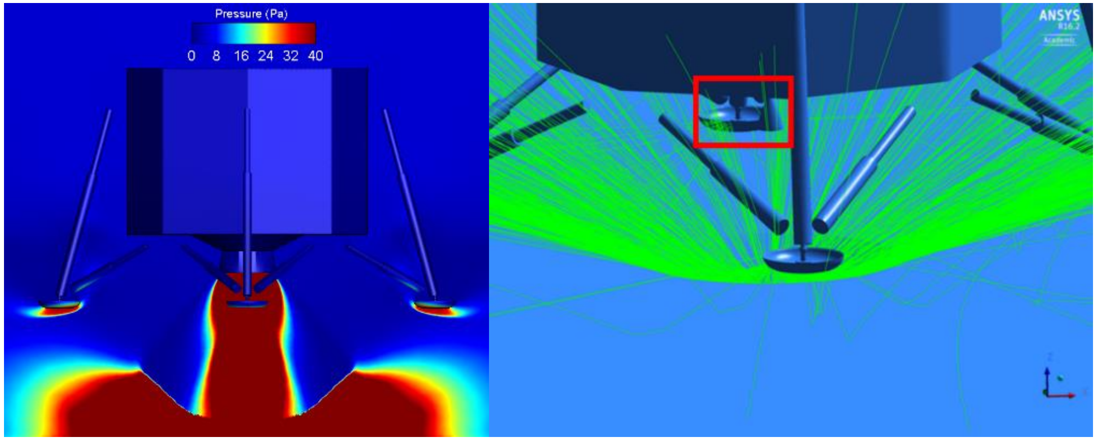
Requirements

19 Passenger (Part 23), Range (500~1,000 km)

Payload (30%), TO/Landing Distance (500~800 m)

Carbon Reduction (75~90%), Low Noise (Below 75 dB)

달착륙선 로켓플룸-Regolith 상호작용



Korean Lunar Lander
(우주핵심연구 2017년)

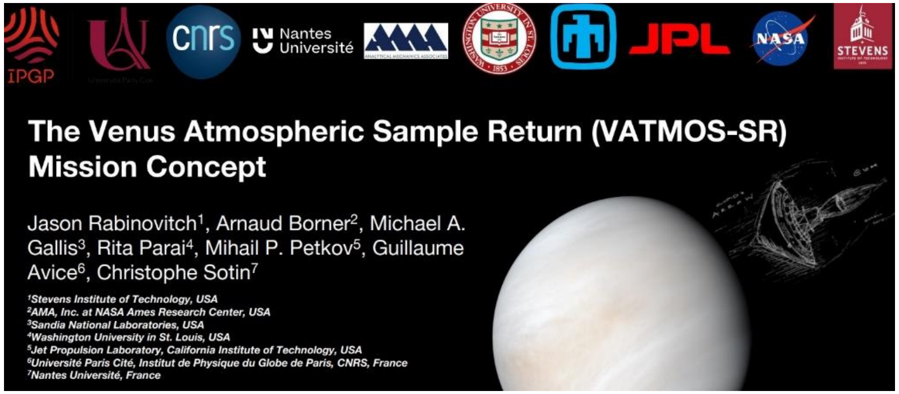
US Intuitive Machines
(2024년 2월)

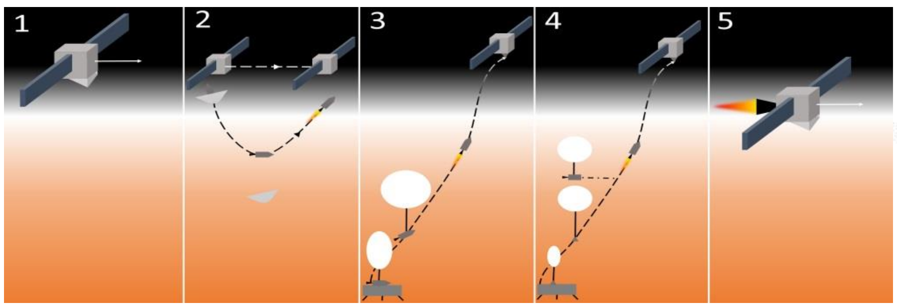
Linchpin Technology

Super Low Altitude Exploration & Sample Return

Connecting the Dots

US VATMOS-SR (2020s)





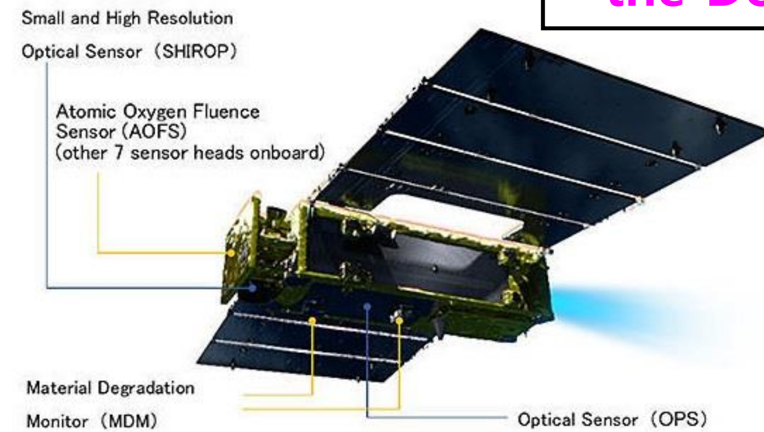
New Venus Super Low Altitude Exploration & Sample Return (SLAESR: 2030~40)

Preliminary mass estimates (kg) for Venus sample return missions

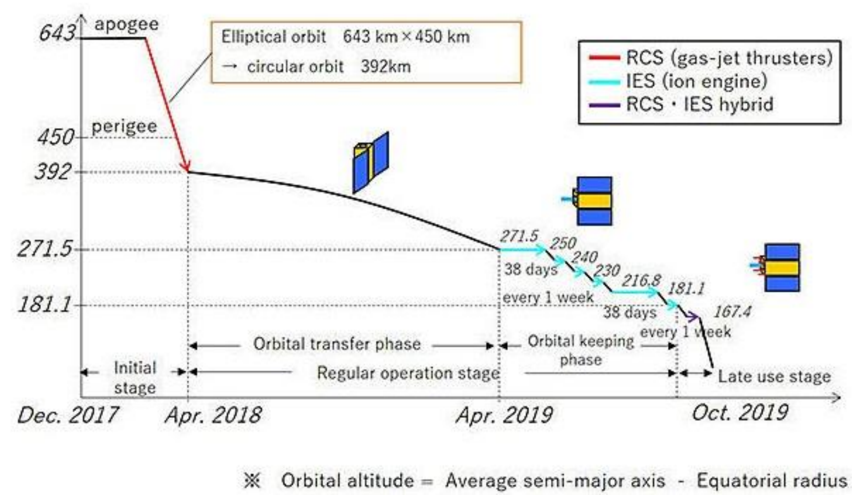
	Atmosphere skimmer	Atmosphere sample return	Surface sample return
Orbiter/return spacecraft	275	400	600
Orbiter propulsion systems and propellants	50	1300	600
Orbiter entry systems (aeroshell or ballute)	75	500	500
Venus ascent vehicle	—	1150	500
Lander and balloon systems	—	—	700
Lander entry systems (deorbit and ballute)	—	—	200
Total systems mass	400	3400	3100

1500-2000 kg

[Illustration of Tsubame in orbit]



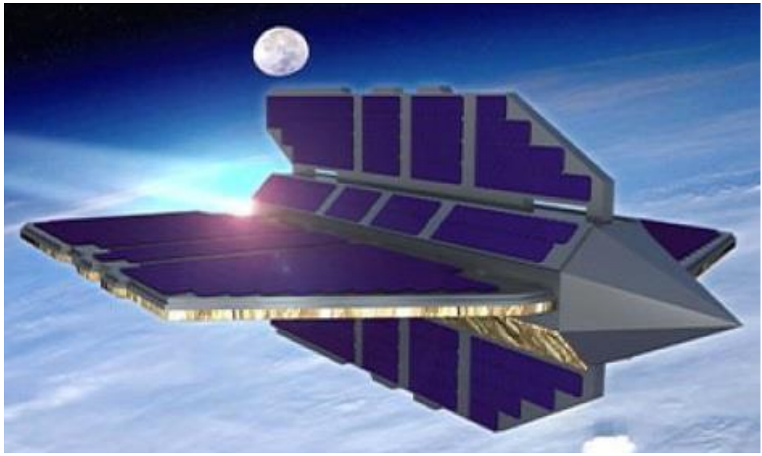
SLATS Orbital Profile]



Super Low Altitude Test Satellite (JAXA, Japan, 30 Dec 2019)

인공위성비행체 설계용 High-fidelity 전산기법

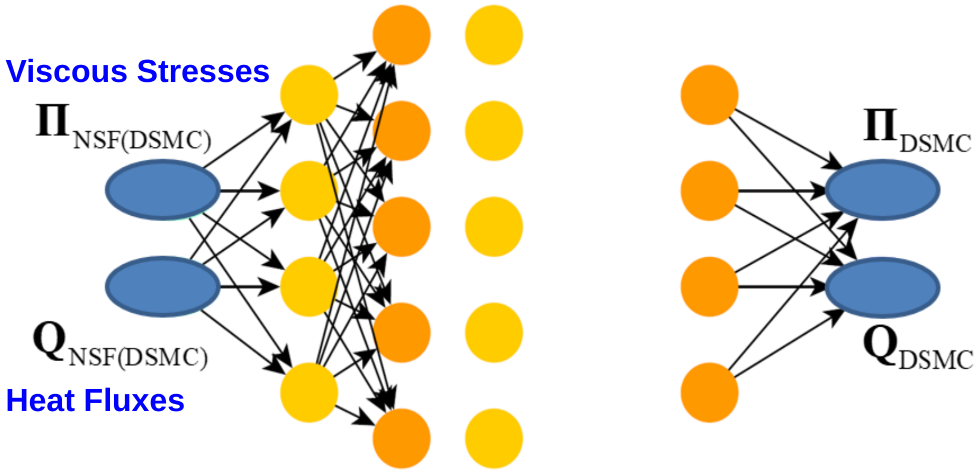
- **US DARPA Otter Program's Orbital Drone (VLEO 90~250 km; 7.5 km/sec; 12 months; Payload 200kg; 2027; Contractor Redwire Corp.)**
- **Missions: Intelligence, surveillance, and reconnaissance (camera, IR sensors, AESA radar)**
- **Electric propulsion system (Electric Propulsion Lab., Colorado): 40 mN/kw, low drag flow-through inlet but inlet capture efficiency classified**
- **A year-long "orbiting wind tunnel" testing; Corrosive atomic oxygen (ceramic material); Aerodynamic solar panel fins**

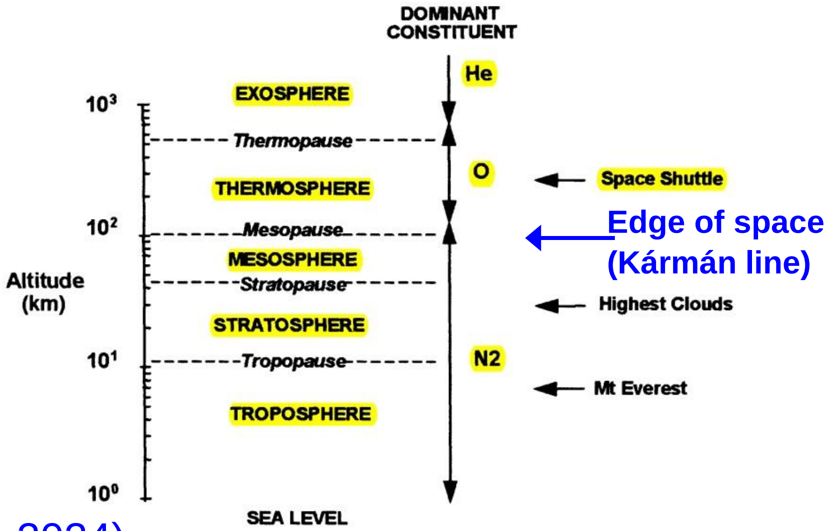


Orbital Drone

(인공위성 비행기)

NN-based Constitutive Relations Obtained from DSMC Data



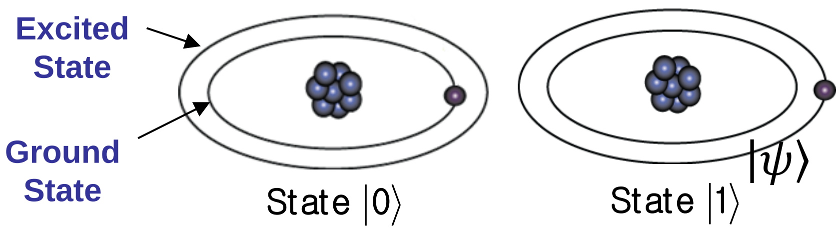


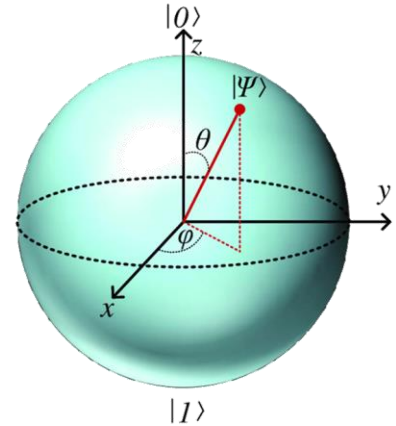
Ultra-fast NN-based FVM-DSMC Solver (Phys. Fluids, 2024)

Quantum Computing

Quantum Computing Concepts: **Superposition, Entanglement, Interference, Measurement, Unitary ($UU^{\dagger}=I$) Operators**

Challenges Toward QCFD: **Non-linear term, Non-unitary operator, Elementwise Multiplication, Initialization, Measurement**





Qubit **Bit**

State Vector: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad |\alpha|^2 + |\beta|^2 = 1$

$$
\begin{aligned}
|\psi\rangle &= |\psi_1\rangle \otimes |\psi_2\rangle \\
&= (\alpha_1|0\rangle + \beta_1|1\rangle) \otimes (\alpha_2|0\rangle + \beta_2|1\rangle) \\
&= \alpha_1\alpha_2|00\rangle + \alpha_1\beta_2|01\rangle + \beta_1\alpha_2|10\rangle + \beta_1\beta_2|11\rangle
\end{aligned}
$$

$$\alpha|0\rangle + \beta|1\rangle \;\text{—}\boxed{X}\text{—}\; \beta|0\rangle + \alpha|1\rangle$$

Quantum NOT gate

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = [1 \quad 0 \quad 0 \quad 0]^T, \quad |01\rangle = |0\rangle \otimes |1\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = [0 \quad 1 \quad 0 \quad 0]^T$$

$$|10\rangle = |1\rangle \otimes |0\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = [0 \quad 0 \quad 1 \quad 0]^T, \quad |11\rangle = |1\rangle \otimes |1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = [0 \quad 0 \quad 0 \quad 1]^T$$

Schrödinger Equation of Wave Function

$$\frac{1}{2m}|p|^2 \qquad + V \qquad = H,$$

$$-\frac{\hbar}{2m}\nabla^2\boldsymbol{\Psi}(t,\boldsymbol{r}) + V(\boldsymbol{r})\boldsymbol{\Psi}(t,\boldsymbol{r}) = i\hbar\frac{\partial\boldsymbol{\Psi}(t,\boldsymbol{r})}{\partial t}$$

Probability of finding a particle with $\boldsymbol{\Psi}$: $\boldsymbol{\Psi}^*\boldsymbol{\Psi}d\boldsymbol{r}$

Expect value of Q: $\langle Q\rangle = \int_{-\infty}^{\infty}\boldsymbol{\Psi}^* Q\boldsymbol{\Psi}d\boldsymbol{r}$

$$\boldsymbol{\Psi}(t,\boldsymbol{r}) \overset{1D}{=} \phi(t)\psi(x),$$

$$\frac{d\phi(t)}{dt} - \frac{H}{i\hbar}\phi(t) = 0 \text{ (time-dependent Schro.)}$$

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2}\left[H - V(x)\right]\psi(x) = 0$$

(time-independent Schro.)

Linearity

Superposition & interference

Time-dependent &
time-independent (eigenvalues)
forms

Separation of variables

Unitary transformation

$$H \rightarrow UHU^\dagger + i\hbar\dot{U}U^\dagger \equiv \breve{H}$$

$$\dot{\phi} = \frac{H}{i\hbar}\phi \;\Rightarrow\; U\dot{\phi} = \frac{UH}{i\hbar}U^\dagger U\phi$$

Using $U\dot{\phi} = \left(\dot{U\phi}\right) - \dot{U}(U^\dagger U)\phi$

$$\left(\dot{U\phi}\right) = \frac{UH}{i\hbar}U^\dagger U\phi - \dot{U}(U^\dagger U)\phi = \frac{\breve{H}}{i\hbar}(U\phi)$$

$$\dot{\breve{\phi}} = \frac{\breve{H}}{i\hbar}\breve{\phi}$$

Quantum Advantage and Interference

Advantage arises from the **exponential dimension (2^n)** of the quantum state, enabling exploration of high-dimensional state spaces.

While superposition enables simultaneous computation, the linearity of quantum mechanics prevents instant identification of a single correct answer. For quantum advantage, the problem must have **a specific structure that quantum algorithms can exploit using interference patterns**.

Quantum coherence maintains a well-defined phase relationship between different states, allowing a system to exist in multiple states simultaneously.

A **quantum interference** is constructed so that the final state represents possible answers, with probabilities determined by phase factors.

The goal of designing an efficient quantum algorithm is to create constructive interference for paths leading to the correct answer and destructive interference for all other paths.

Consider two paths from A to B:

Classical: $P_1,\ P_2 \ \Rightarrow\ P = P_1 + P_2$

Quantum: $|\alpha_1|e^{i\varphi_1},\ |\alpha_2|e^{i\varphi_2} \ \Rightarrow\ P = |\alpha_1 + \alpha_2|^2$

$$= |\alpha_1|^2 + |\alpha_2|^2 + 2|\alpha_1||\alpha_2|\cos(\varphi_2 - \varphi_1) = P_1 + P_2 + \boxed{2\sqrt{P_1P_2}\cos(\varphi_2 - \varphi_1)}$$

Quantum CFD (Approaches)

- Nonlinear **QODE** solver [1] $\frac{d\boldsymbol{u}}{dt} = f(\boldsymbol{u}), \quad u(t+\Delta t) = u(t) + \int_t^{t+\Delta t} f(u(z))dz$

  NS PDEs → ODEs

- Hybrid Variational Approaches (**VQA**) [2]

  Express the flow field in the variational form $u(x,t;\lambda) = \sum_n u_n(t)\phi_n(x;\lambda)$ Cost function in QC, optimization of variational parameters λ in CC

- **Carleman Linearization** [3] Suitable for Boltzmann equations, not for NSEs

  Nonlinear DEs → Linearized DEs

- Encoding Nonlinearity in **Computational Basis** [4]

  For calculating nonlinear terms, the solution is converted to computational basis, and converted back to amplitudes once computed

- Pure quantum algorithm using **multiple copies** approach (present ACML approach)

  Creating multiple copies of velocities to calculate non-linear terms

[1] F. Gaitan, Finding flows of a Navier–Stokes fluid through quantum computing. **npj Quantum Information**, 6 (1), 1-6, in, DOI, 2020.
[2] M. Lubasch, J. Joo, P. Moinier, M. Kiffner, D. Jaksch, Variational quantum algorithms for nonlinear problems, **Physical Review A** 101 (2020) 010301.
[3] J.-P. Liu, H.Ø. Kolden, H.K. Krovi, N.F. Loureiro, K. Trivisa, A.M. Childs, Efficient quantum algorithm for dissipative nonlinear differential equations, **PNAS** 118 (2021) e2026805118.
[4] R. Steijl, Quantum Circuit Implementation of Multi-Dimensional Non-Linear Lattice Models, **Applied Sciences** 13 (2022) 529.

Boltzmann Kinetic Equation (BKE)

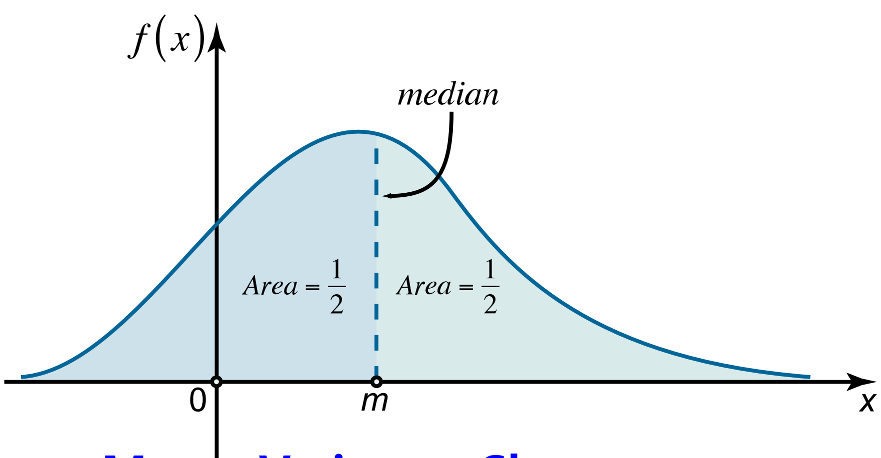
- **Assumptions**; 1) the mean free path >> the effective range of the intermolecular forces; 2) the velocities of the colliding particles are uncorrelated (molecular chaos and break of time reversal)
- A first-order **partial differential** equation with an **integral** collision term

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right) f(t,\mathbf{r},\mathbf{v})=\frac{1}{Kn}C[f,f_2]$$

Only two effects! (Simplicity)

Movement — Collision (or Interaction)

Kinematic — Dissipation



Mean, Variance, Skewness, ...

$$C[f,f_2] = \text{Gain (scattered into)} - \text{Loss (scattered out)}$$

$$= \left(\frac{\delta f}{\delta t}\right)^{+} - \left(\frac{\delta f}{\delta t}\right)^{-}$$

$$\sim \int |\mathbf{v}-\mathbf{v}_2| (f^* f_2^* - f f_2) d\mathbf{v}_2$$

Complexity (Nonlinearity) out of Simplicity

$$\rho\mathbf{u} = \langle m\mathbf{v}f(t,\mathbf{r},\mathbf{v})\rangle$$

where $\langle\cdots\rangle = \iiint \cdots dv_x dv_y dv_z$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right) f(t,\mathbf{r},\mathbf{v}) = C[f, f_2]$$

Differentiating the statistical definition $\rho\mathbf{u} \equiv \langle m\mathbf{v}f(t,\mathbf{r},\mathbf{v})\rangle$ *with time* and *then combining* with BTE ($t, \mathbf{r}, \mathbf{v}$ are independent and $\mathbf{v} = \mathbf{u} + \mathbf{c}$)

$$\frac{\partial}{\partial t}\langle m\mathbf{v}f\rangle = \left\langle m\mathbf{v}\frac{\partial f}{\partial t}\right\rangle = -\langle m(\mathbf{v}\cdot\nabla f)\mathbf{v}\rangle + \langle m\mathbf{v}C[f, f_2]\rangle$$

$[\mathbf{A}]^{(2)}$: Traceless symmetric part of tensor $\mathbf{A}$

Here $-\langle m(\mathbf{v}\cdot\nabla f)\mathbf{v}\rangle = -\nabla\cdot\langle m\mathbf{v}\mathbf{v}f\rangle = -\nabla\cdot\{\rho\mathbf{u}\mathbf{u} + \langle m\mathbf{c}\mathbf{c}f\rangle\}$

After the decomposition of the stress into pressure and viscous shear stress $\mathbf{\Pi}$

$\mathbf{P} \equiv \langle m\mathbf{c}\mathbf{c}f\rangle = p\mathbf{I} + \mathbf{\Pi}$ where $p \equiv \langle m\mathrm{Tr}(\mathbf{c}\mathbf{c})f/3\rangle$, $\mathbf{\Pi} \equiv \langle m[\mathbf{c}\mathbf{c}]^{(2)} f\rangle$,

and using the collisional invariance of the momentum, $\langle m\mathbf{v}C[f, f_2]\rangle = 0$,

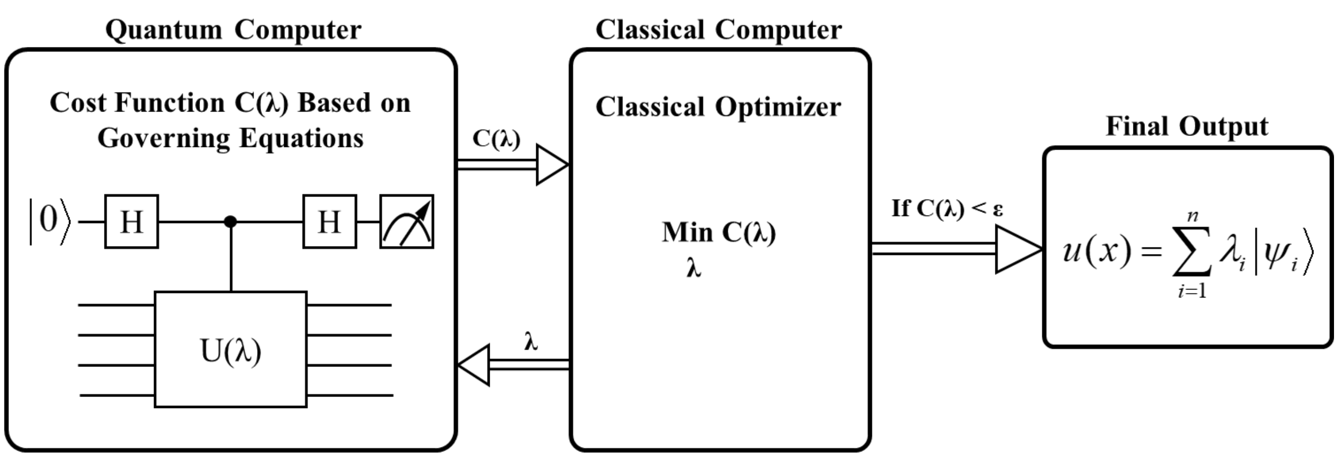
we have

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u} + p\mathbf{I} + \mathbf{\Pi}) = 0.$$

Exact consequence of the original BKE!

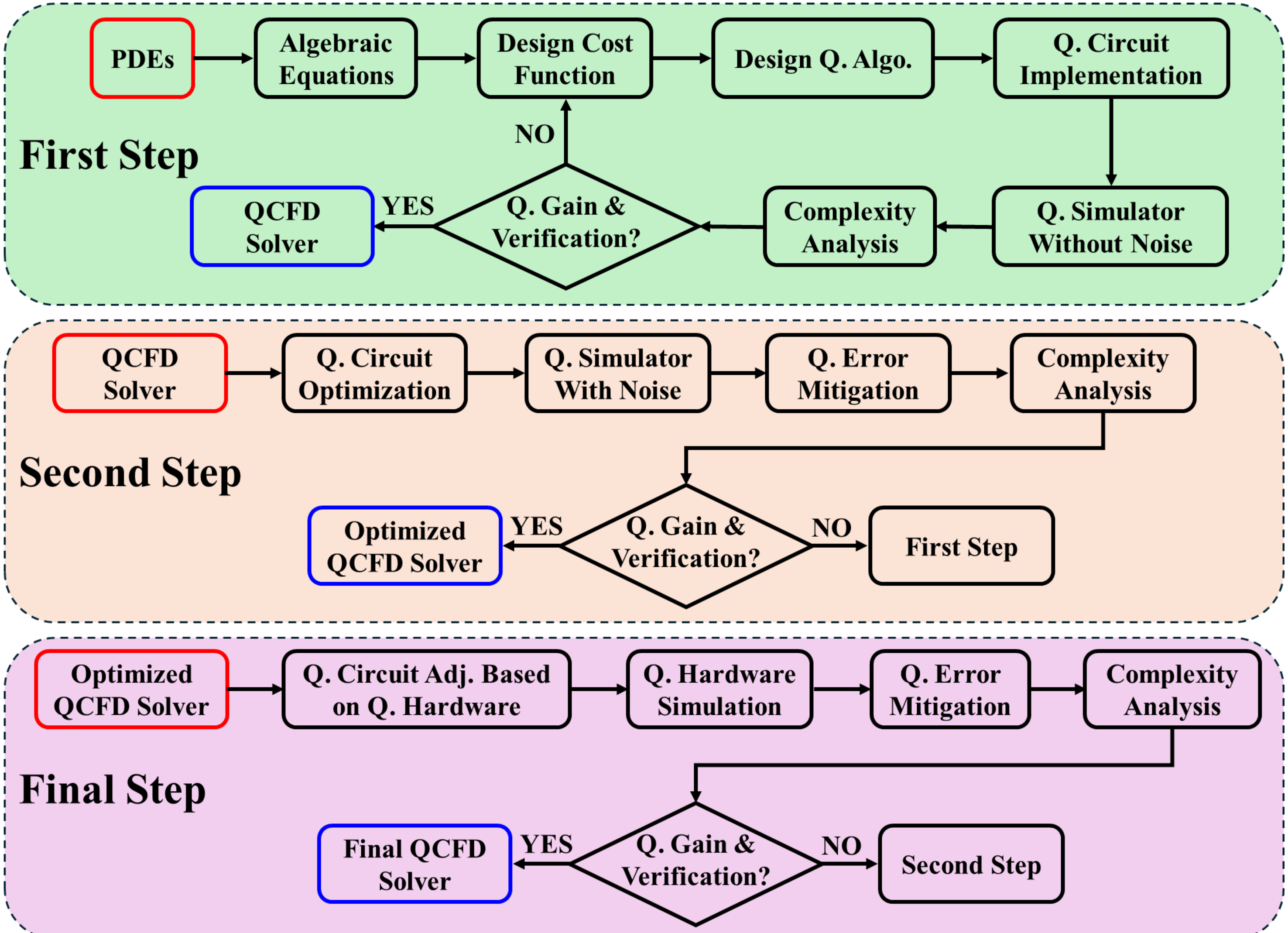
Quantum CFD: Variational Approach

- A naive approach to computing a nonlinear product on a quantum computer would involve measuring the full velocity field, then calculating nonlinear terms in CC, and finally reinitializing in QC.
- These steps would need to be performed for every time step, so an exponential speedup over a classical computer is unlikely with this approach.
- The alternative is a variational quantum algorithm (VQA), which is a hybrid quantum-classical algorithm, but potentially exponentially faster.
- In VQA, evaluation of the cost function C(λ) is delegated to a QC, while the optimization of variational parameters λ is performed on a CC.



Flow Variables in Variational Form $u(x) = \sum_{i=1}^{n} \lambda_i |\psi_i\rangle$

Variational Quantum Algorithm (VQA)

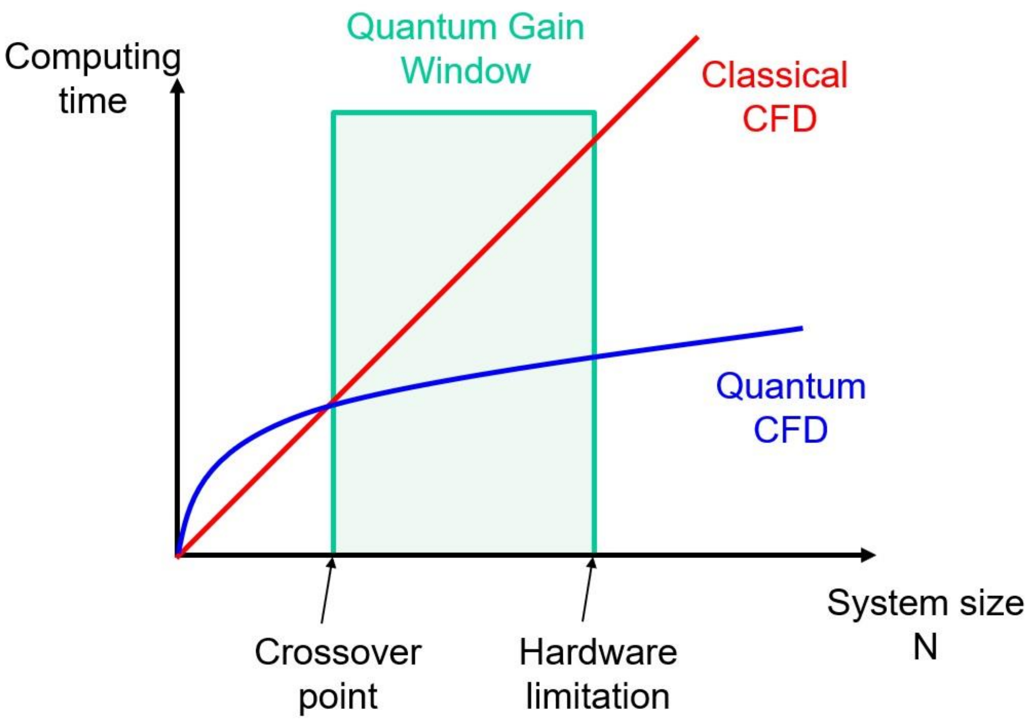


Quantum Gain

Quantum gain (exponential or polynomial speed-up) can be measured by comparing the computational complexity of quantum algorithms and classical algorithms.

The number of calls to a specific function in the quantum algorithms can be compared with the classical counterpart. The number of calls will be scaled with the size of the system (N) and error rate (ε).

Total cost ~ N_iter * N_shots * N_gate



Quantum DSMC (Direct Simulation Monte Carlo)

Analysis of complexity and prospective quantum approach for designing quantum algorithm for DSMC

DSMC Steps	**Complexity**	**Approach**
Initialization	$(N_s+N_u)N_pN_t$	Quantum State Preparation
Movement	$N_sN_pN_t$	Linear Combination of Unitaries
Boundary Condition	$N_sN_pN_t$	Quantum Amplitude Estimation Algorithm (Not Finalized yet)
Indexing	$N_sN_pN_t$	Quantum Amplitude Estimation Algorithm (Not Finalized yet)
Binning	$N_sN_pN_t$	Quantum Amplitude Estimation Algorithm (Not Finalized yet)
Collision	$\mathrm{Max}((N_s+N_u)N_p)N_t$	Quantum Singular Value Transformation / Encoding in Computational Basis
Sampling	$(N_s+2N_u)N_p\ N_t$	Time History technique and Amplitude Interference
Random Number Generation	-	Quantum Random Number Generator Based on Hadamard Gates

N_p=number of particles

N_s=3 (locations)

N_u=3 (velocities)

N_t=number of iterations

We generated QRNG (**Quantum Random Number Generator**) and compared the pre-generated pseudo-RNGs for its quality in terms of Chi-square and Kolmogorov value.

The Challenge of No-cloning due to Nonlinearity

No-cloning theorem **prevents** the use of (temporary) copies, temp= u, to compute the value of u^2 as $u\times$temp.

Burger's equation is the best model for studying **inherent nonlinearity** in fluid dynamics.

$$\frac{\partial u}{\partial t}+\frac{\partial}{\partial x}\left(\frac{u^2}{2}+\Pi\right)=0$$

NCCR-Burgers' eq. (1999)

$$\xleftarrow[p\sim u^2]{\rho\approx 1}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial}{\partial x}\left(\rho u^2+p\right)+\frac{\partial \Pi}{\partial x}=0$$

1D Approx. in Spatial Coordinates

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\boldsymbol{u}\\ E\end{bmatrix}+\nabla\cdot\begin{bmatrix}\rho\boldsymbol{u}\\ \rho\boldsymbol{uu}+p\mathbf{I}\\ (E+p)\boldsymbol{u}\end{bmatrix}+\nabla\cdot\begin{bmatrix}0\\ \boldsymbol{\Pi}\\ \boldsymbol{\Pi}\cdot\boldsymbol{u}+\mathbf{Q}\end{bmatrix}=0$$

$$\Pi q(\Pi)=(\Pi+1)\Pi_0 \text{ where } q(\Pi)=\frac{\sinh\Pi}{\Pi}$$

2nd-order Approx. for Nonlinear Coupled Constitutive Relations (NCCR)

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)f(t,\mathbf{r},\mathbf{v})=\frac{1}{Kn}C\left[f,f_2\right]$$

$$\Pi=\Pi_0\equiv-\mu\frac{\partial u}{\partial x}$$

$$\boxed{\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=\mu\frac{\partial^2 u}{\partial^2 x}}$$

Burgers' eq. (1948)

Cornerstone

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=0 \longrightarrow \frac{\partial u}{\partial t}+c\frac{\partial u}{\partial x}=0$$

Inviscid Burgers' eq. Linear advection eq.

Pure Quantum Algorithm for Burgers Eqn.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \mu\frac{\partial^2 u}{\partial x^2}$$

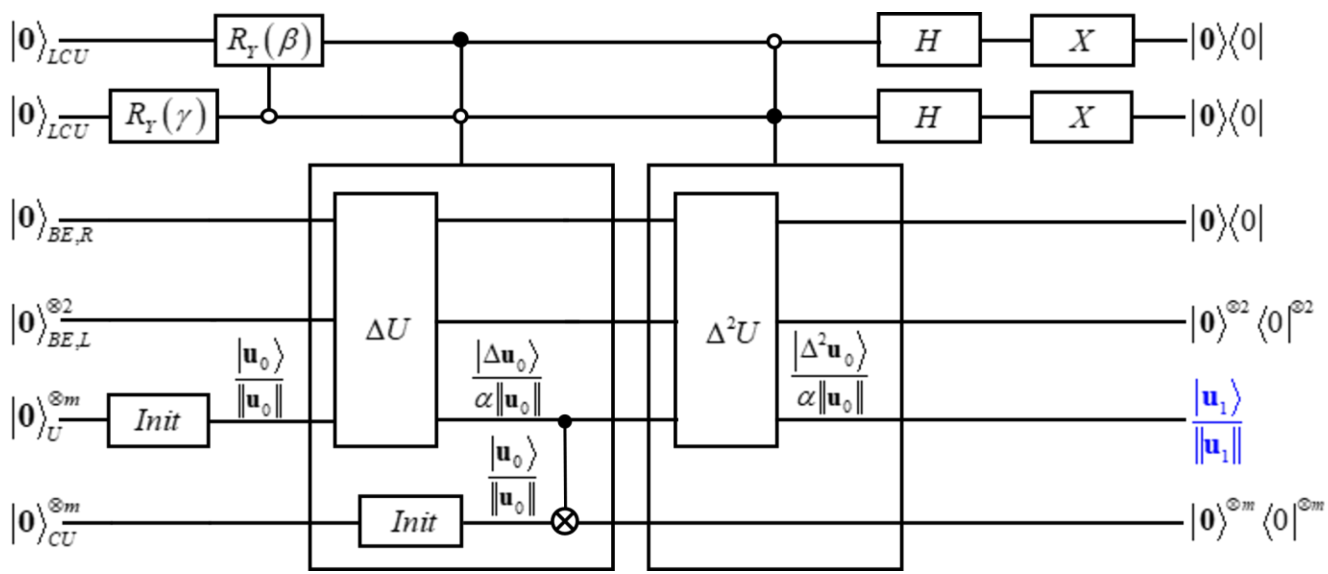
Linear combination of vectors handled by linear combination of unitaries

Velocity gradients (non-unitary transformation) using the block-encoding technique

$$\boldsymbol{u}^{n+1} = \boldsymbol{u}^n - \Delta t\left(\boldsymbol{u}^n \odot \boldsymbol{g}^n\right) + \mu\ \Delta t\left(\boldsymbol{h}^n\right)$$

Non-linear multiplication of ***u*** and its derivative handled by employing multiple copies of ***u***

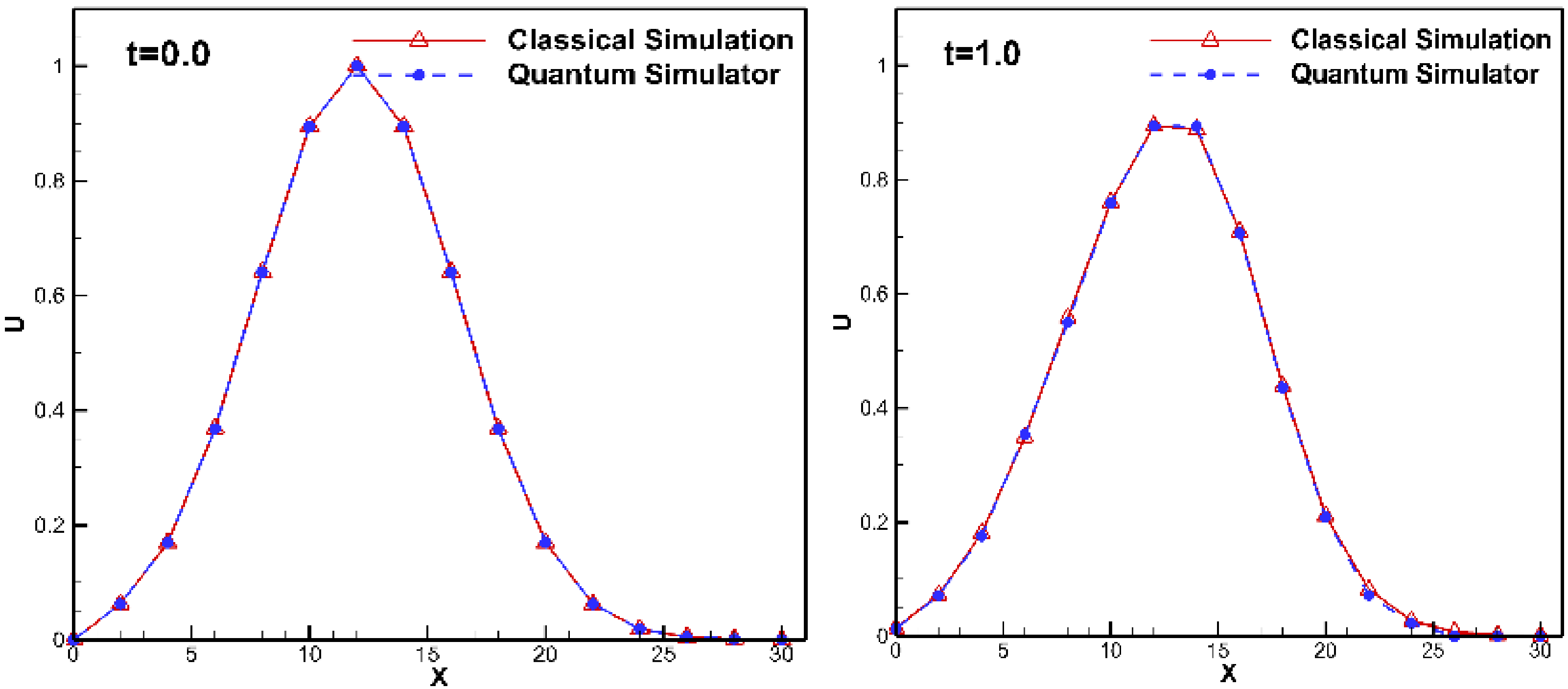
Non-unitary elementwise multiplication using quantum Hadamard product technique



Esmaeilifar, E., Ahn, D., Myong, R. S., "Quantum Algorithm for Nonlinear Burgers' Equation for High-speed Compressible Flows," *Physics of Fluids*, Vol. 36, 106110, Oct. 2024. (Desk Accept Article)

Pure Quantum Algorithm for Burgers Eqn.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \mu \frac{\partial^2 u}{\partial x^2}$$



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The Prospects of Quantum Computing

$$2^{10} = 10^3,\ 2^{20} = 10^6,\ 2^{30} = 10^9,\ \cdots,\ 2^{100} = 10^{30}$$

- NISQ (Near-term Intermediate-Scale Quantum) → Early FTQC (Fault-tolerant Quantum Computing) with ISQ (Intermediate-Scale Quantum) → FTQC with logical qubits with QEC (Quantum Error Correction)
- Rather than scaling up to more qubits with noise, developing devices with fewer error-corrected logical qubits
- A shift toward applications and expertise in different application fields can bring new perspectives.
- Google's roadmap is focused on error correction and quality improvement rather than the number of qubits.
- Google quantum AI $5 million XPRIZE quantum applications: 3-year competition to drive development of quantum algorithms towards quantum advantage for applications realizing a positive real-world impact (novel algorithm, new application, and enhanced performance).
- IQM roadmap: Demonstration of QEC in 2028, FTQC in 2030.