Quantum Radiance Field – Quantum Hybrid 3D Vision

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How do we recognize 3D Scene?

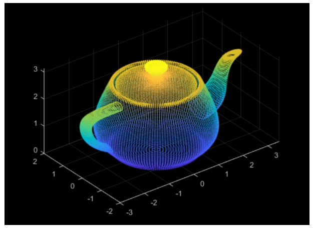
- Input: Retina / Camera = 2D Image

- Recognition: 3D Scene Concept

- Output: Human Memory / Monitor = 2D Image

How do we recognize 3D Scene?

- Recognition: 3D Scene Concept
  - **Explicit Scene Representation:**
    e.g., 3D Point Cloud, Polygon/Mesh, Voxel
    - 3D 객체의 정보를 일일이 저장
    - 해상도의 영향을 받음 – 품질과 n^3의 데이터 용량 사이의 trade-off
  - **Implicit Scene Representation:**
    Function: $\mathcal{F}:(\boldsymbol{x},\boldsymbol{\phi}) \rightarrow \boldsymbol{Image}$
    - 객체를 저장하는 것이 아닌 생성 정보를 저장
    - 함수의 형태이므로 인접한 pixel에 대해 미분 가능
    - 생성 정보의 모델링이 쉽지 않음 (NP)



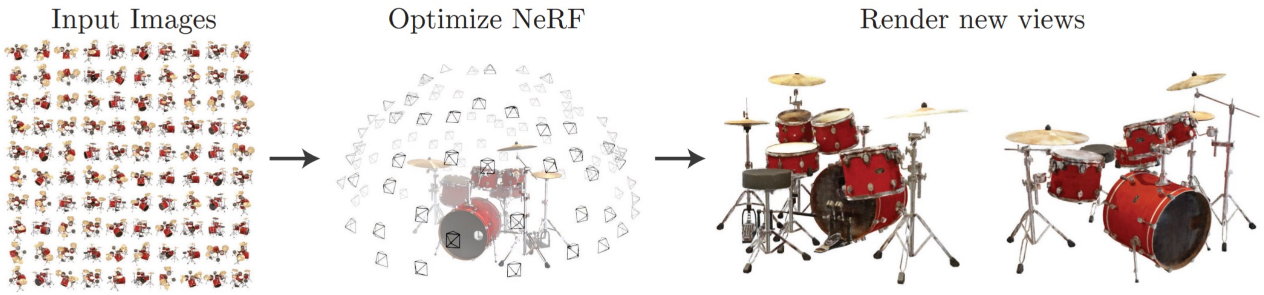
3D Point Cloud

Polygon/Mesh

Voxel

NeRF: Neural Radiance Field

- NeRF: Neural Network를 생성함수로 사용한 Representation
    - 여러 각도에서 찍은 사진을 input으로 하여 Scene을 나타내는 Neural Network를 Training
    - 학습 결과로 3D Scene 용량 5MB 내외



arXiv:2003.08934 / NeRF: Neural Radiance Fields (matthewtancik.com)

〈Introduction〉

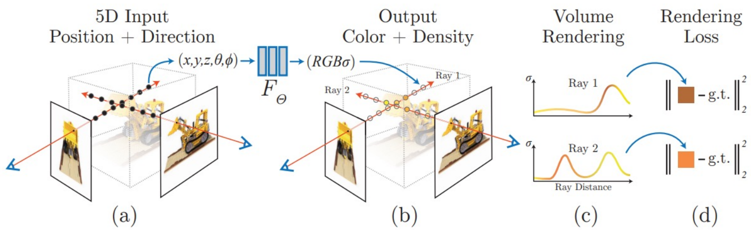
NeRF: Neural Radiance Field

[arXiv:2003.08934 / NeRF: Neural Radiance Fields (matthewtancik.com)]

⟨Introduction⟩

NeRF: Neural Radiance Field

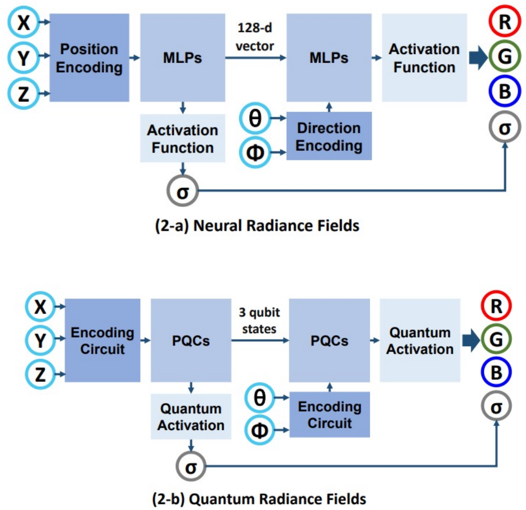
- NeRF의 구조
  - Viewer의 위치, 방향 -〉 5차원 input (x, y, z, θ, ϕ)
  - Multi Layered Perceptron F_Θ (Neural Network)
  - Volume Rendering -〉 2D image
  - Loss 계산 및 Optimize (Training)



- MLP의 단점
  - High Frequency Function에 대한 underfitting
    Solution -〉 Positional Encoding (주기함수 확장)
  - 한 Scene을 학습 시키는데에 1-2일 소요

QRF: Quantum Radiance Field

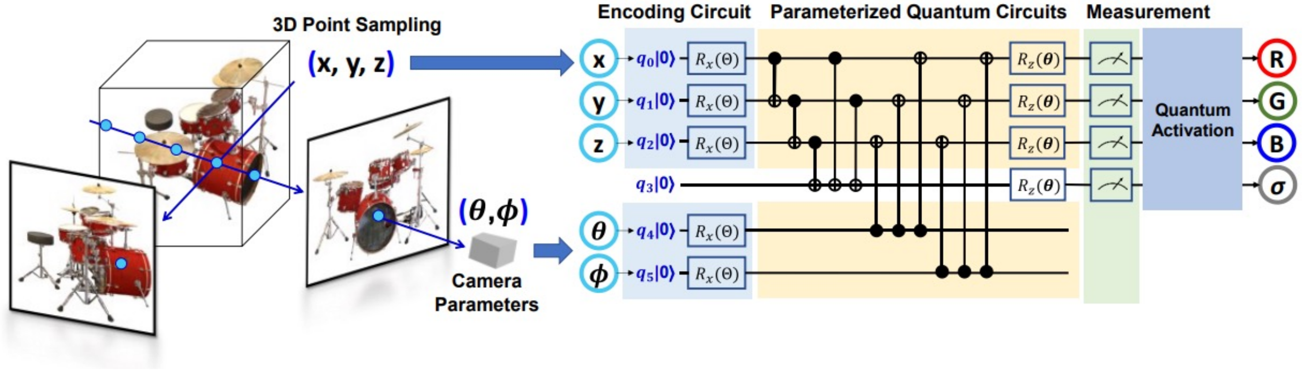
- QRF의 핵심 아이디어
  - **MLP -> PQC**
  - Quantum Activation Function
  - Quantum Encoding
- 차별점
  - High Frequency Function에 대한 MLP의 단점을 우회할 수 있다.
  - MLP에 비해 Layer 개수가 적게 소요되므로 렌더링 속도가 빨라질 수 있다.
  - Positional Encoding 부분을 Quantum Encoding으로 간단하게 대체 가능하다.



[[2211.03418] QRF: Implicit Neural Representations with Quantum Radiance Fields (arxiv.org)]

QRF: Quantum Radiance Field

- Circuit 구조
  - input (x, y, z, θ, ϕ) -〉 Quantum Encoding
  - Trainable PQC
  - Quantum Activation -〉 Loss
  - Optimization



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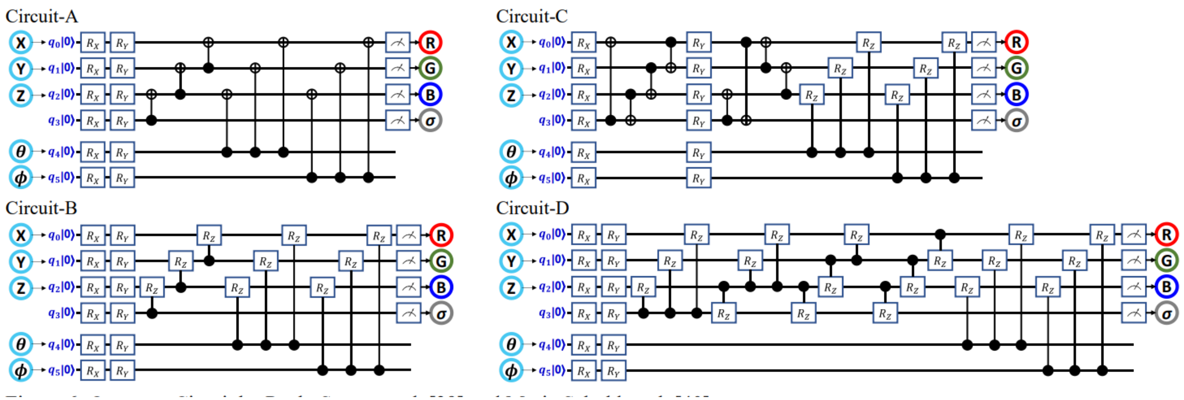
QRF: Quantum Radiance Field

- PQC 후보
  - 4가지




```python
n_qubits = 6
dev = qml.device('default.qubit', wires=n_qubits, shots=1000)

def encoding(inputs):
    qml.AngleEmbedding(features=inputs, wires=range(n_qubits), rotation='X')

def pqc(parameters):
    parameter_cursor = 0

    for wire in range(n_qubits):
        qml.RX(parameters[parameter_cursor + wire], wires=wire)
    parameter_cursor += n_qubits

    for wire in range(n_qubits):
        qml.RY(parameters[parameter_cursor + wire], wires=wire)
    parameter_cursor += n_qubits -1

    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(3, 2))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(3, 1))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(3, 0))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(2, 3))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(1, 2))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(1, 0))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(2, 3))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(1, 2))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(0, 1))

    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(4, 2))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(4, 1))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(4, 0))

    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(5, 2))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(5, 1))
    qml.CRZ(parameters[parameter_cursor:=parameter_cursor+1], wires=(5, 0))


@qml.qnode(dev, interface="torch")
def qrf_circuit(inputs, weights):
    encoding(inputs)
    pqc(weights)
    return [qml.expval(qml.PauliX(i)) for i in range(4)]
```

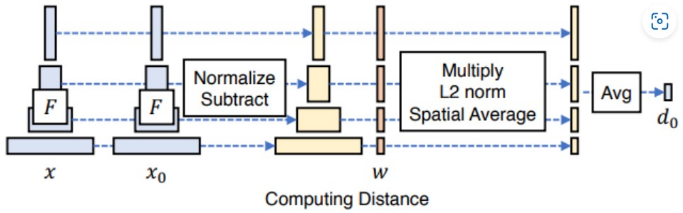
[2211.03418] QRF: Implicit Neural Representations with Quantum Radiance Fields (arxiv.org)

QRF: Quantum Radiance Field

- Evaluation Metrics
  - PSNR: 영상 화질 평가, 픽셀 오차
  - SSIM: 영상 화질 평가, 휘도/대비 오차
  - LPIPS: VGG Feature 오차
  - FPS: 렌더링 속도

$$PSNR = 10 \cdot \log_{10}\left(\frac{MAX_I^2}{MSE}\right) \quad MSE = \frac{\sum_{M,N}[I_1(m,n) - I_2(m,n)]^2}{M * N}$$

$$\mathrm{SSIM}(\mathbf{x}, \mathbf{y}) = [l(\mathbf{x}, \mathbf{y})]^{\alpha} \cdot [c(\mathbf{x}, \mathbf{y})]^{\beta} \cdot [s(\mathbf{x}, \mathbf{y})]^{\gamma}$$



$$d(x, x_0) = \sum_l \frac{1}{H_l W_l} \sum_{h,w} ||w_l \odot (\hat{y}^l_{hw} - \hat{y}^l_{0hw})||_2^2$$

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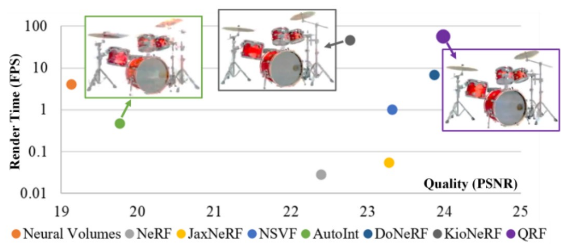
QRF: Quantum Radiance Field

- Experiment
  - Classical: Tesla V100 GPU
  - Quantum: Xanadu Borealis QPU (현재 비공개)

Table 4: Quantitative results on each scene from the Synthetic-NeRF [13], Synthetic-NSVF [15], and Tanks and Temples [36]. We highlight the top 3 results in each column are color coded as Top 1, Top 2 and Top 3.

Dataset	Synthetic-NeRF [13]				Synthetic-NSVF [15]				Tanks and Temples [36]			
Evaluate Metrics	PSNR	SSIM	LPIPS	FPS	PSNR	SSIM	LPIPS	FPS	PSNR	SSIM	LPIPS	FPS
SRN [7]	22.26	0.846	0.170	0.909	24.33	0.882	0.141	1.304	24.10	0.847	0.251	0.250
Neural Volumes [8]	26.05	0.893	0.160	3.330	25.83	0.892	0.124	4.778	23.70	0.834	0.260	1.000
NeRF [13]	31.01	0.947	0.081	0.023	30.81	0.952	0.043	0.033	25.78	0.864	0.198	0.007
JaxNeRF [14]	31.69	0.953	0.049	0.045	31.49	0.958	0.026	0.065	27.94	0.904	0.168	0.013
NSVF [15]	31.75	0.953	0.047	0.815	35.18	0.979	0.015	0.095	28.42	0.907	0.153	0.163
AutoInt [17]	25.55	0.911	0.170	0.380	26.63	0.916	0.090	0.545	22.28	0.766	0.278	0.116
DoNeRF [18]	32.50	0.957	0.037	5.635	32.29	0.962	0.027	8.085	27.02	0.805	0.174	1.715
FastNeRF [19]	29.97	0.941	0.053	172.42	29.78	0.946	0.083	224.71	24.92	0.792	0.213	47.67
KioNeRF [20]	31.02	0.950	0.051	38.46	33.37	0.970	0.020	55.07	28.41	0.910	0.091	11.68
QRF	32.65	0.960	0.029	47.26	35.44	0.980	0.014	67.70	29.65	0.820	0.085	14.36



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