ANALOG CONTROL OF THE DIAMOND QUANTUM PROCESSOR

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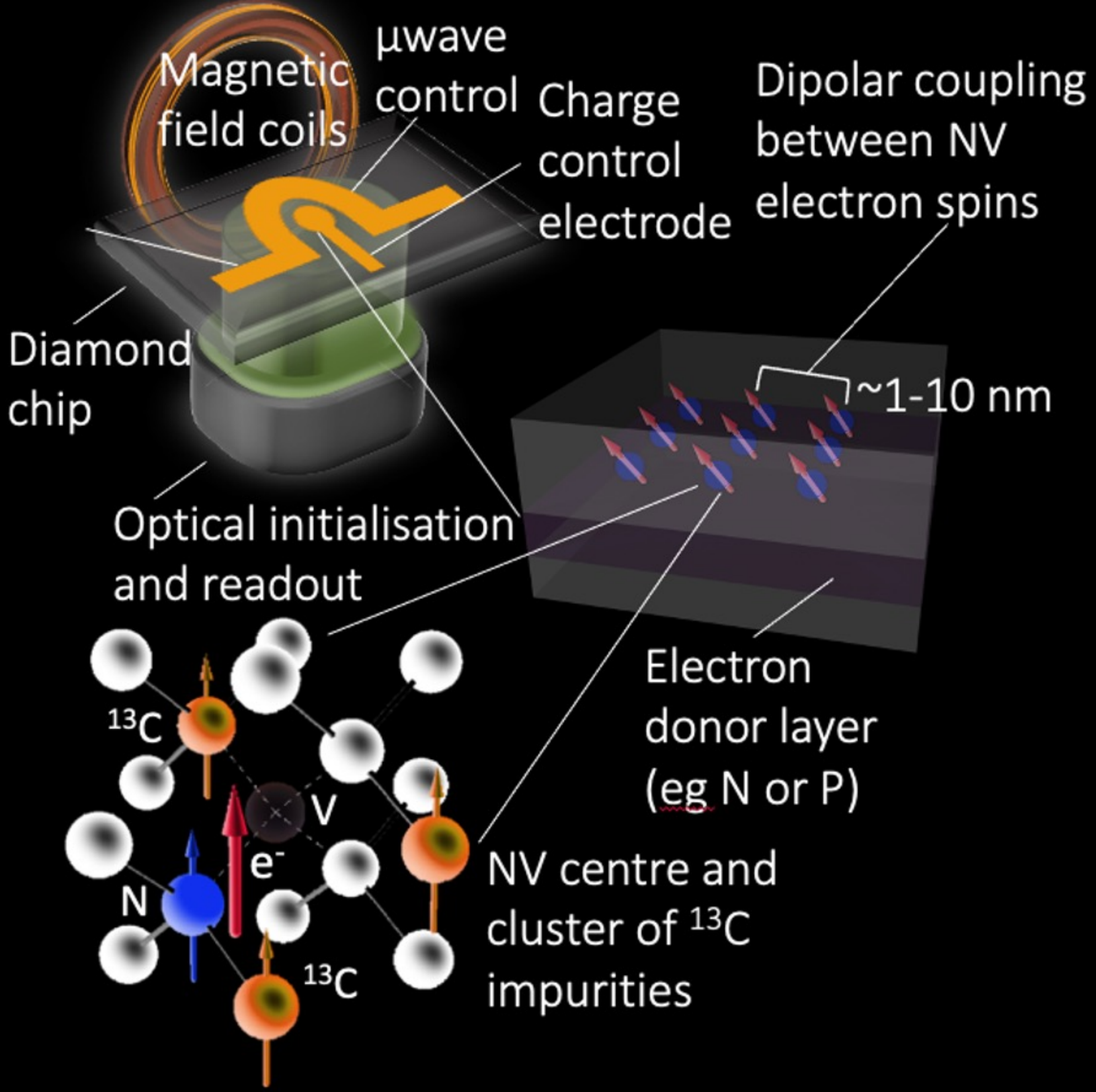
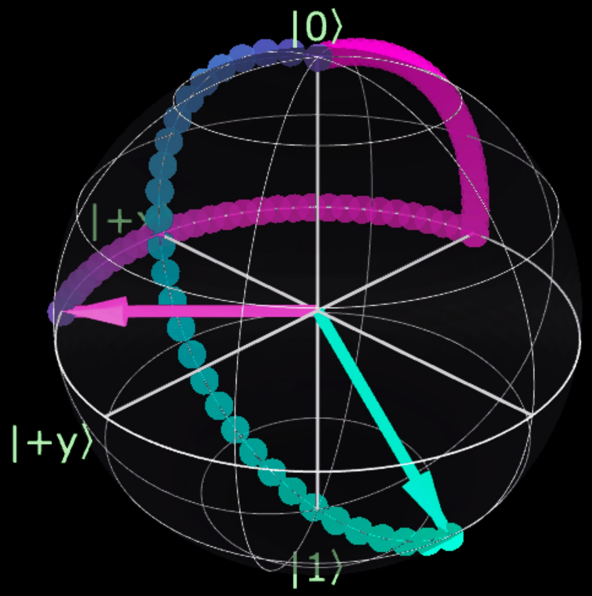
DIAMOND QUANTUM COMPUTING

- Uses the NV-centre, an optical defect.
- Long coherence time at room temperature.
- Controlled via MW and RF pulses.
- Quantum Brilliance is in the process of designing a fully scalable array of NV centres.
- Currently able to easily fabricate diamond samples with many NV centres.
- Currently, computation using diamond is only done via the gate paradigm- perhaps there are alternatives…



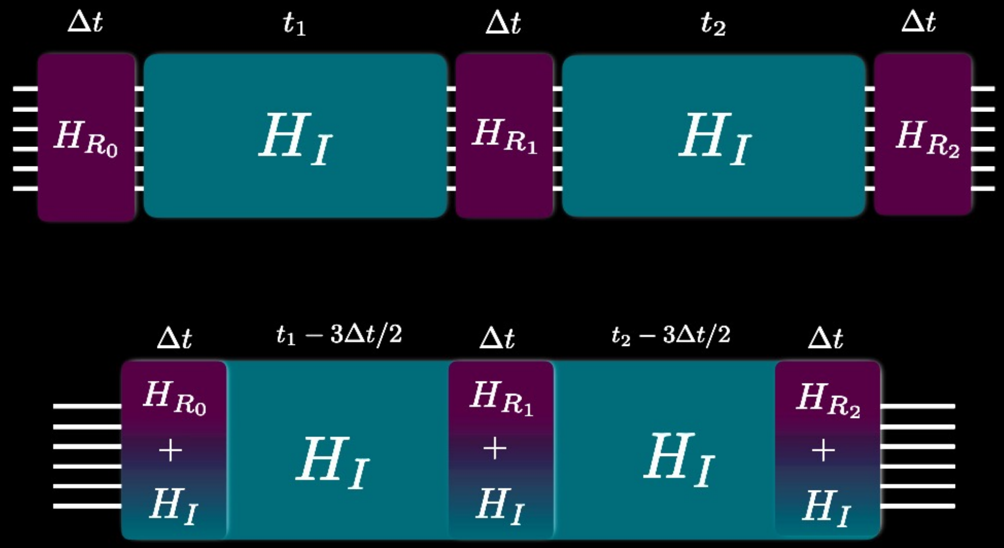
ANALOG QUANTUM COMPUTING

- Sequence of gates can be thought of a single rotation about an arbitrary axis.
- No gates- rotate straight to end result.
- Continuous driving, rather than discrete pulses.



- Potential error robustness
- AQC compilation is difficult.
- The challenge is an opportunity.

- ParityQC and D-Wave- quantum annealing
- Not the same as CVQC encoding.
- Better for diamond: DAQC- fusing gates and annealing together.

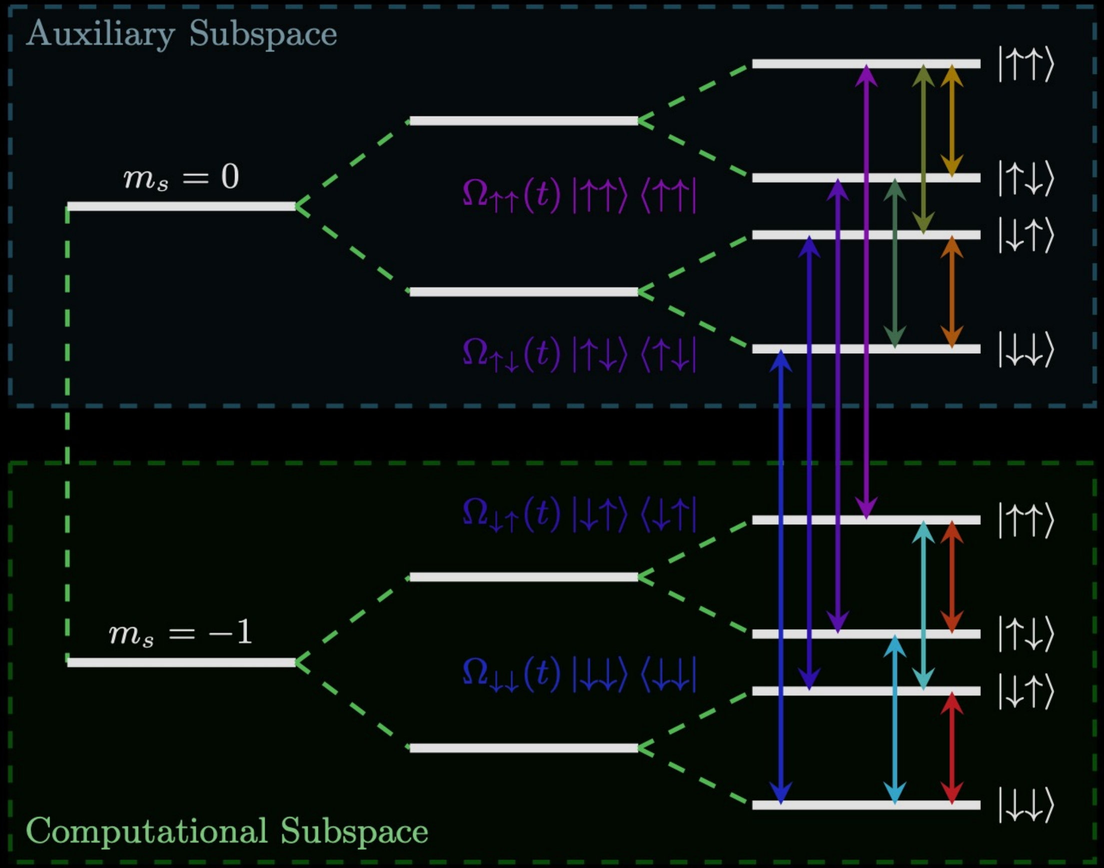


- *Expand quantum annealing work.*
- *Begin to address analog compilation challenges.*
- *Implement DAQC on diamond.*

HAMILTONIAN

$$H_S = D\left(S_z^2 - \frac{2}{3}\right) + \gamma_e\big(S_z B_0 + S_x B_1(t)\big) + \sum_i \vec{S}\cdot\vec{A}_{i,z}\cdot\vec{I}_i - \gamma_i\left(I_{i,z}B_0 + I_{i,x}B_1(t)\right)$$

2 QUBIT LEVELS



Carbon-13 sites aligned to the 0th order between $m_s = -1$ and $m_s = 0$ will be used,

$$H_A \approx \frac{\gamma_e B_0 - D}{2}\sigma_z + \frac{\gamma_e}{\sqrt{2}}B_e(t)\sigma_x - |0_e\rangle\langle 0_e|H_0 - |-1_e\rangle\langle -1_e|H_{-1}$$

$$H_0 = \sum_i \gamma_i B_{0,i} I_{i,z} + \gamma_i B_{1,i}(t) I_{i,z}$$

$$H_{-1} = \sum_i \omega_i I_{i,z} + \gamma_i B_{1,i}(t) I_{i,x}$$

Transform into the interaction picture…

THE ISING MODEL

$$H_C = H_S(t) + |0_e\rangle\langle 0_e|H_0 + |-1_e\rangle\langle -1_e|H_{-1}$$

$$H_S(t) = \frac{\gamma_e}{\sqrt{2}} B_1(t) \sum_\alpha (\sigma_x \cos \Lambda_{\kappa_\alpha} t - \sigma_y \sin \Lambda_{\kappa_\alpha} t) \left(\prod_i \mathrm{m}_{\kappa_{\alpha i}} I_{i,z} + \frac{1}{2} \right)$$

Collect like terms to write each transition as a linear combination of nuclear spin operators multiplied by applied control fields…

$$H_{Ising} = S_x \left(\sum_{i<j} \Omega_{i,j}(t) I_{i,z} I_{j,z} + \sum_i \Omega_i(t) I_{i,z} \right) + \sum_i \Xi_i(t) I_{i,x} + \Xi_i(t) I_{i,y}$$

Two qubit example:

$$\kappa_\alpha = \{\uparrow\uparrow, \uparrow\downarrow, \downarrow\uparrow, \downarrow\downarrow\}$$

$$\begin{aligned} H_S(t) = \frac{\gamma_e}{\sqrt{2}} B_1(t) \Big\{ & \frac{1}{4}(I_{1z} I_{2z} + I_{1z} + I_{2z} + 1) \\ & \times (\sigma_x \cos \Lambda_{\uparrow\uparrow} t - \sigma_y \sin \Lambda_{\uparrow\uparrow} t) \\ & + \frac{1}{4}(-I_{1z} I_{2z} + I_{1z} - I_{2z} + 1) \\ & \times (\sigma_x \cos \Lambda_{\uparrow\downarrow} t - \sigma_y \sin \Lambda_{\uparrow\downarrow} t) \\ & + \frac{1}{4}(-I_{1z} I_{2z} - I_{1z} + I_{2z} + 1) \\ & \times (\sigma_x \cos \Lambda_{\downarrow\uparrow} t - \sigma_y \sin \Lambda_{\downarrow\uparrow} t) \\ & + \frac{1}{4}(I_{1z} I_{2z} - I_{1z} - I_{2z} + 1) \\ & \times \sigma_x \cos \Lambda_{\downarrow\downarrow} t - \sigma_y \sin \Lambda_{\downarrow\downarrow} t \Big\} \end{aligned}$$

Gather Λs together in linear combination to produce $\Omega_{1,2}$, Ω_1, Ω_2, Ξ_1 and Ξ_2.

TWO-CHANNEL DAQC

As per the Rodriguez formula, single qubit gates can be written as,

$$U_{R_\phi} = e^{iR_\phi \hat{n} \cdot \vec{\sigma}}$$

All entanglement can be done with an Ising coupling gate.

$$U_{I_{zz}} = e^{\vec{I_z} \overleftrightarrow{\Theta} \vec{I_z}}$$

Where,

$$\vec{I_z} = (I_{1z}, I_{2z}, \dots, I_{nz})$$

$$\overleftrightarrow{\Theta} = \begin{bmatrix} \Theta_{11} & \cdots & \Theta_{1n} \\ \vdots & \ddots & \vdots \\ \Theta_{n1} & \cdots & \Theta_{nn} \end{bmatrix}$$

Also, as the **Ising model commutes with itself** all entangling gates *and* single qubit gates can be performed in a single step- provided the hardware is capable of rotations about any arbitrary axis.

Diamond computers can do this.

	1 QUBIT GATE	**2 QUBIT GATE**	**1 QUBIT GATE**	…
Qubit 1	$R(\phi_1, \hat{n})$	$R_{zz}(\Theta_{12})$	$R(\phi_1, \hat{n})$	…
Qubit 2	$R(\phi_2, \hat{n})$	$R_{zz}(\Theta_{12})$	$R(\phi_2, \hat{n})$	…

New way to control diamond quantum processors: Continuous driving of superposition of electron spin states.

EXAMPLE: ANALOG QFT

$$U(t) = e^{S_x\left(\sum_{i<j}\Omega_{i,j}(t) I_{i,z} I_{j,z} + \sum_i \Omega_i(t) I_{i,z}\right) + \sum_i \Xi_{i,x}(t) I_{i,x} + \sum_i \Xi_{i,y}(t) I_{i,y}}$$

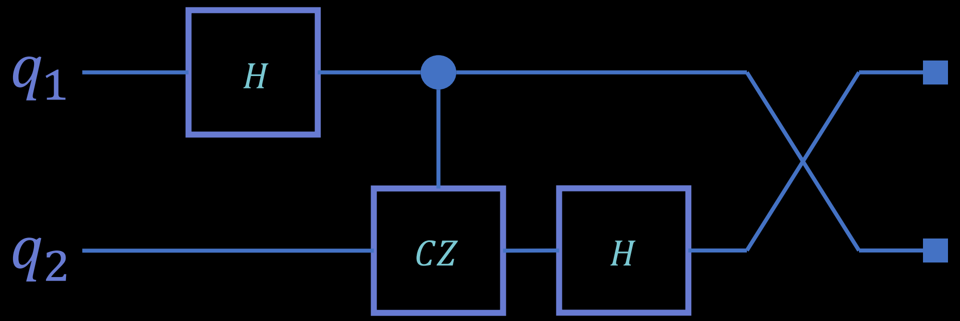
$$\Downarrow$$

$$U(t) = e^{S_x(\Omega_{zz,12}(t) I_{1,z} I_{2,z} + \Omega_{z,1}(t) I_{1,z} + \Omega_{z,2}(t) I_{2,z} + \Lambda_0) + \Xi_{1,x}(t) I_{1,x} + \Xi_{2,x}(t) I_{2,x} + \Xi_{1,y}(t) I_{1,y} + \Xi_{2,y}(t) I_{2,y}}$$

$$\Downarrow$$

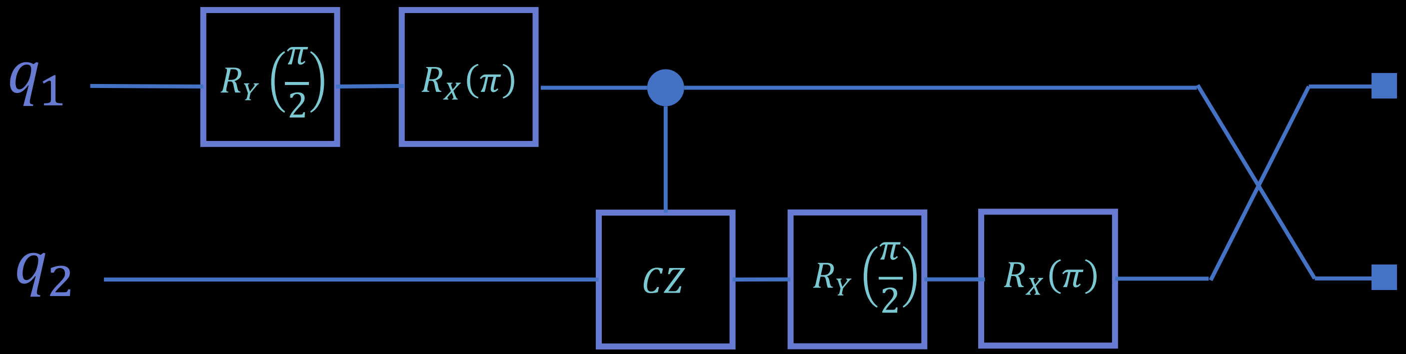
$$F_4 = \frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & i & -1 & -i \\ 1 & -1 & 1 & -1 \\ 1 & -i & -1 & i \end{bmatrix}$$

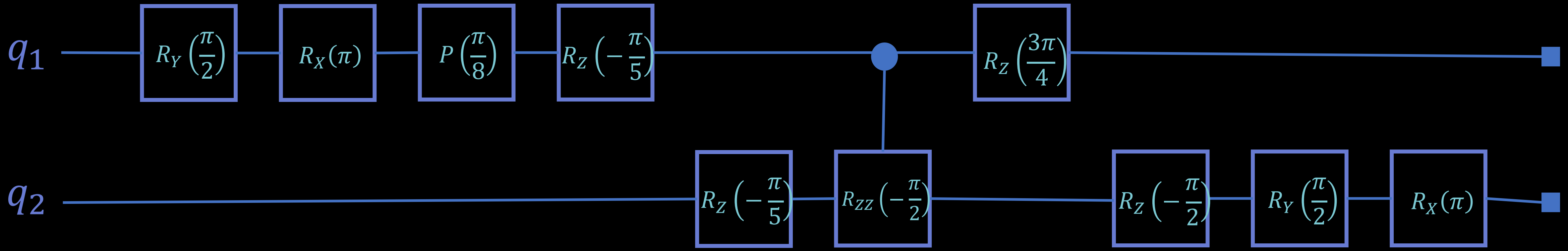
2-QUBIT QFT



Gate-based QFT compiled to native diamond gates. Circuit depth increases.

Splitting up the CZ gate gives an Ising coupling gate.





REDUCE DEPTH

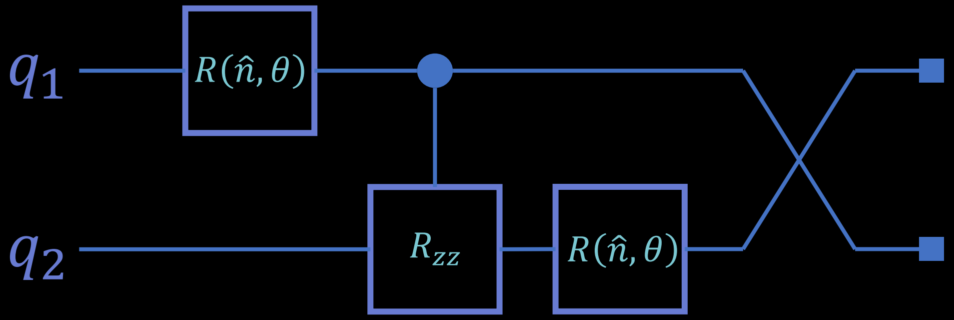
Invoking the Rodriguez formula, this can be compacted back into 3 gates.

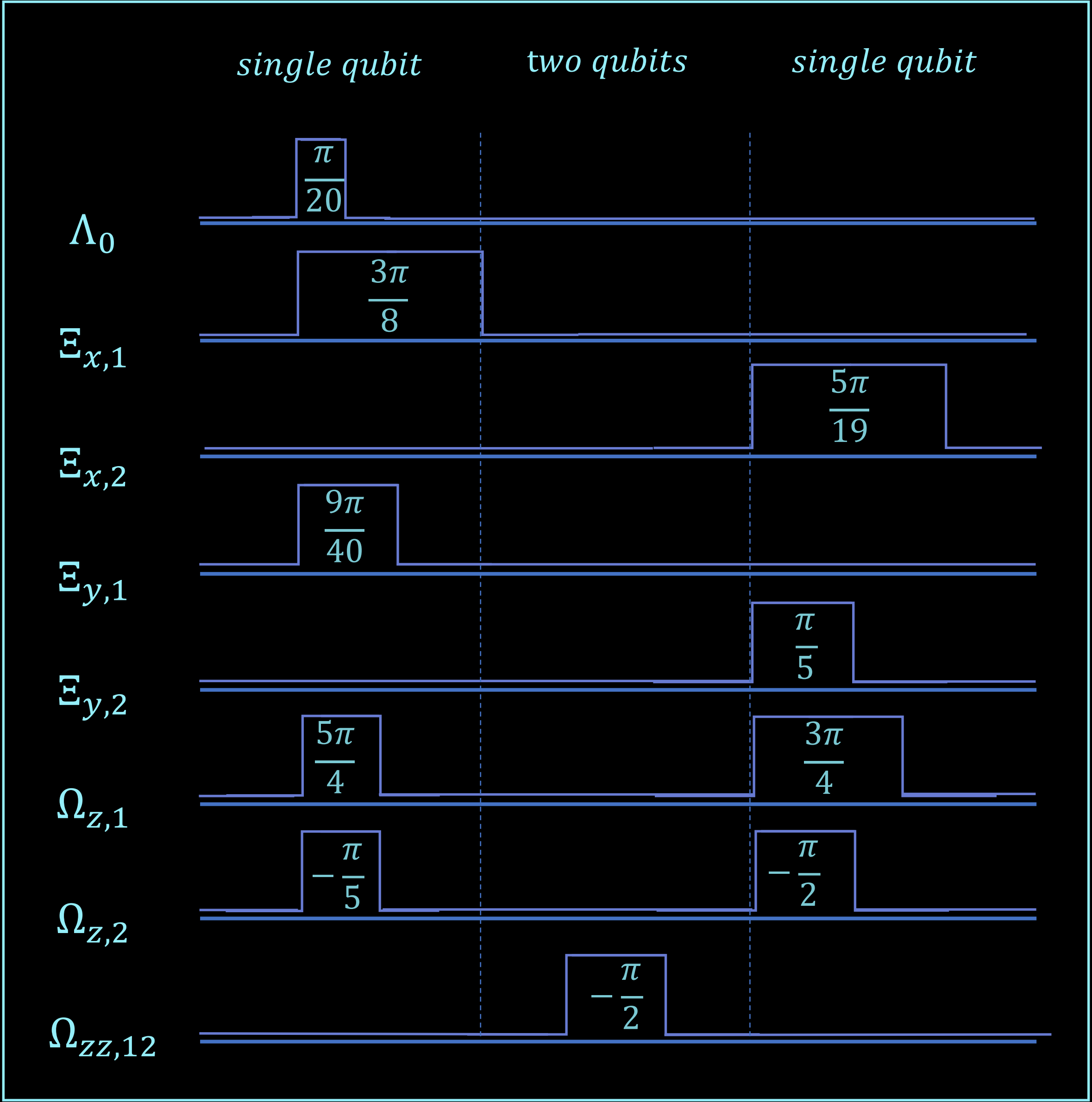
$$U_{R_\phi} = e^{iR_\phi \hat{n}\cdot\vec{\sigma}}$$

$$R(\hat{n},\theta) = (\hat{Y},\theta_{y_1})(\hat{X},\theta_{x_1})(\hat{Z},\theta_{z_1})$$

$$R(\hat{n},\theta) = e^{-\frac{i}{2}\theta\hat{n}\cdot\vec{\sigma}} = e^{-\frac{i}{2}\vec{R}\cdot\vec{\sigma}}$$

$$\vec{R} = \theta n_x\vec{x} + \theta n_y\vec{z} + \theta n_z\vec{z}$$

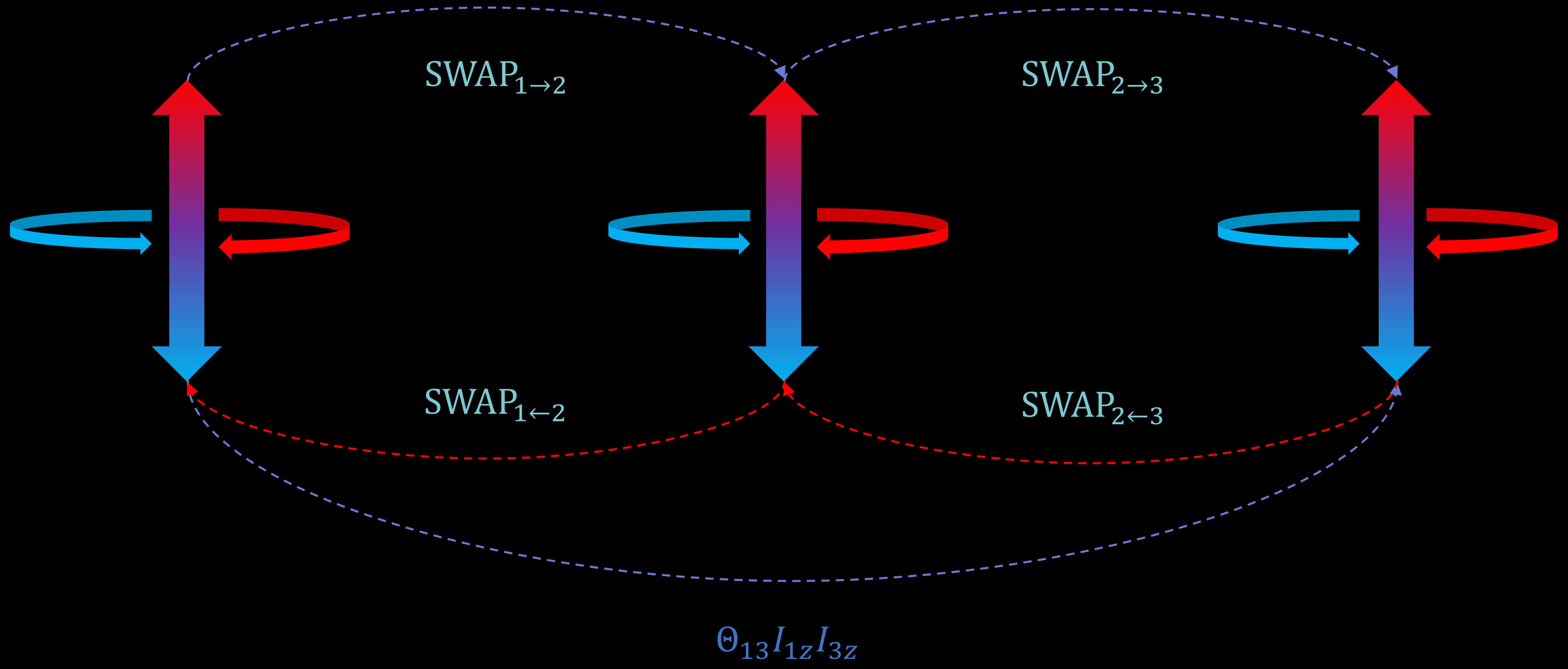




Where each of the components of $\hat{n}$ becomes our pulse components.

CONNECTIVITY

$$e^{i(\Theta_{12}I_{1z}I_{2z}+\Theta_{23}I_{2z}I_{3z}+\Theta_{13}I_{1z}I_{3z})} = e^{i(\Theta_{12}I_{1z}I_{2z}+\Theta_{23}I_{2z}I_{3z})}.\mathrm{SWAP}_{2\to3}.\, e^{i(\Theta_{13}I_{1z}I_{3z})}.\mathrm{SWAP}_{3\to2}$$



FUTURE WORK

- See how this formulations performs error-wise compared to gate model implementations of the Fourier transform.
- See how number of SWAP gates scales with size and limited connectivity- and if this outweighs potential benefits.
- Expand past the hybrid model, looking to full universal AQC.
- Investigate what this means for optimal control.
- Find systematic way to compile AQC pulses for diamond.

THANK YOU

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