Institute for Quantum Information Science at the University of Calgary

Learned Feedback Control Mechanisms for a Quantum System

Alexander Hentschel

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Content

Introduction to Quantum Information

Quantum Computation & Information

study of information processing tasks that can be accomplished using quantum mechanical systems

Quantum mechanical system: (usually) system containing only few particles

Possible encodings of information:
- energy level of electrons
- electron spin
- polarization of light

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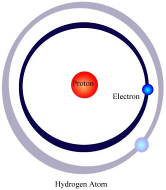

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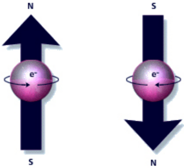

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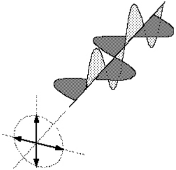

Encoding in polarization of light:

- logical 0: $\leftrightarrow$ (horizontal polarization)
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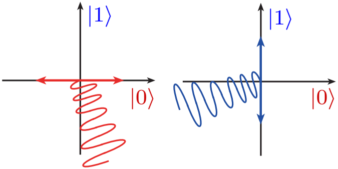

Superposition

Probabilistic interpretation: (Bohr & Heisenberg, 1927)

Probability to measure qubit $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$ in

- state $|0\rangle$: $P(|0\rangle) = |\alpha|^2$
  state $|1\rangle$: $P(|1\rangle) = |\beta|^2$

State $|\tilde{\Psi}\rangle$ after measurement with

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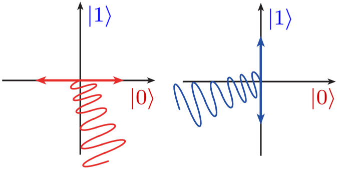
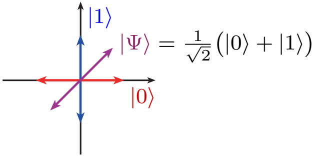


Superposition

mixture of $|0\rangle$ and $|1\rangle$:

example: $|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle + |1\rangle\big)$



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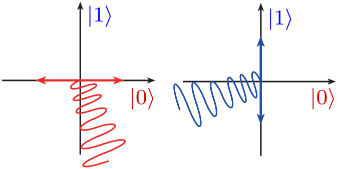

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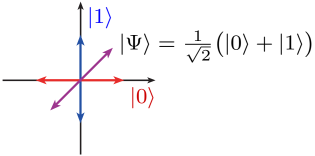
general state of a Qubit: $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$

with $\alpha, \beta \in \mathbb{C}, \; |\alpha|^2 + |\beta|^2 = 1$



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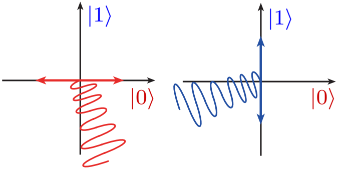

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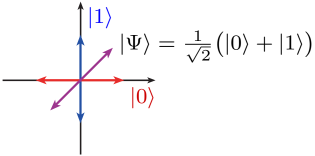

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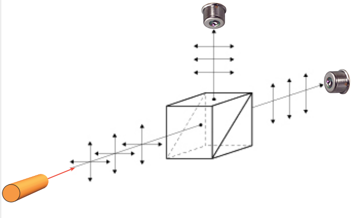

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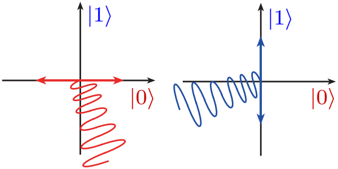

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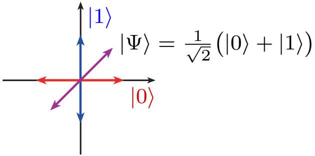

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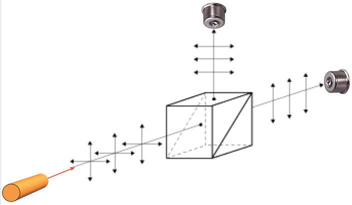

Quantum Register $|\Psi\rangle$

with N qubits: 2^N classical states

- $|\Psi\rangle$ can be in any superposition of 2^N classical states

$$|\Psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_{2^N-1}|2^N - 1\rangle$$

Quantum Operations

- Quantum Parallelism:
  Operations act on *all* basis states of $|\Psi\rangle$
- Micro Reversibility:
  in microsystem (usually) all processes reversible

Quantum operations = linear & invertible functions
(unitary matrices)

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\Big(|0\rangle + |1\rangle\Big)$$
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$$\frac{1}{\sqrt{2}}\Big(\frac{\sqrt{3}}{2}|0\rangle + \frac{1}{2}|1\rangle - \frac{1}{2}|0\rangle + \frac{\sqrt{3}}{2}|1\rangle \Big)$$

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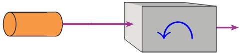
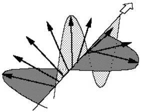
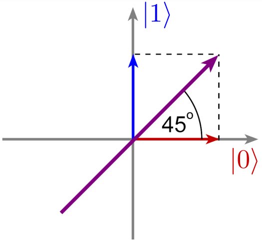


non-linear crystal

rotates polarization by fixed angle :





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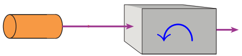

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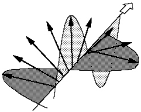

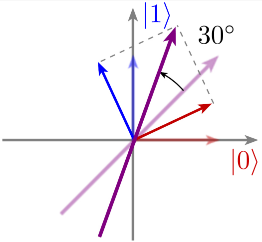

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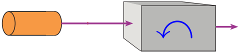

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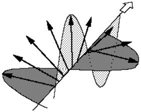

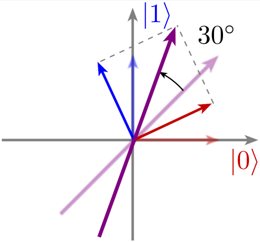

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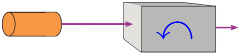

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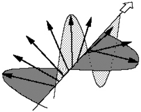

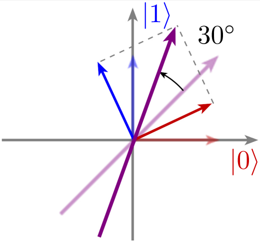

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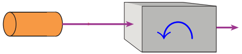

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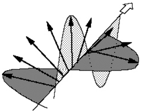

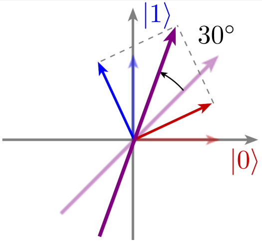

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Quantum register: $|\Psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle + \alpha_2|2\rangle + \cdots + \alpha_{2^N-1}|2^N - 1\rangle$

summary so far:

- reading out quantum register:
  random outcome $|i\rangle$ with probability according to weight α_i
- after reading a quantum register:
  information in $|\Psi\rangle$ destroyed (after measurement $|\Psi\rangle = |i\rangle$)

Question: Can one copy the state $|\Psi\rangle$ of a quantum register?

Answer: No!

No Cloning Theorem

There is no operation which can copy a quantum state $|\Psi\rangle$:

$$\textsc{Copy}\Big(\underbrace{|\Psi\rangle}_{\text{quantum state}} \otimes \underbrace{|\emptyset\rangle}_{\text{target register}}\Big) = |\Psi\rangle \otimes |\Psi\rangle$$

Quantum Algorithms

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Quantum Learning: Motivation

Artificial Intelligence

methods for classical computation

- Bayesian Reasoning
- Neural Networks
- Evolutionary Algorithms

⋮

Quantum Information

provides extend computational model

- Superposition:
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Gravitational Wave Detection

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Quantum Learning: Possible Settings

Quantum state: $|\Psi\rangle = \alpha_0|\psi_0\rangle + \cdots + \alpha_{2^N-1}|\psi_{2^N-1}\rangle$

Full control over quantum system

Can prepare and measure $|\Psi\rangle$ repeatedly

- apply quantum tomography $|\Psi\rangle$:
  similar to classical case, all system parameters known
- but: exponentially runtime in N

Partial control over quantum system

Measurement perturbs $|\Psi\rangle$

- evolution of system is primarily driven by AI
- only partial information available

Implement learning on quantum level

- quantum parallelism: apply AI-algorithm to every $|\psi_i\rangle$

$|\Psi\rangle$

AI

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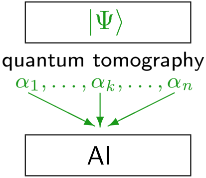

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Can prepare and measure $|\Psi\rangle$ repeatedly

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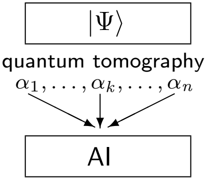

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Measurement perturbs $|\Psi\rangle$

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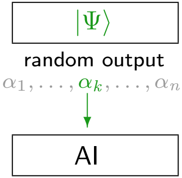

Implement learning on quantum level

- quantum parallelism: apply AI-algorithm to every $|\psi_i\rangle$

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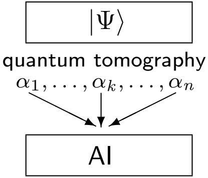

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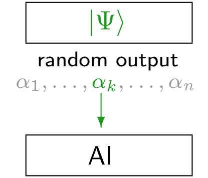

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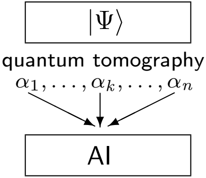

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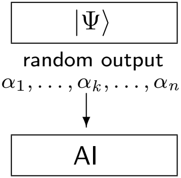

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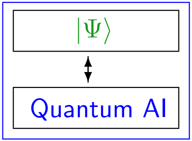


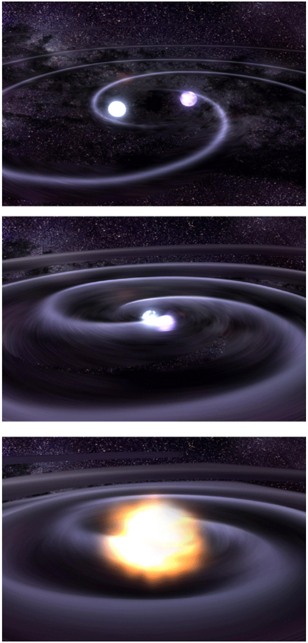
Possible application:

Detection of Gravitational Waves

- move with speed of light
  resource: time $\Leftrightarrow$ N pulses
- extremely weak: $\sim 10^{-20}$
  valuable resource: sensitivity

- LIGO, Washington, USA

- Detection: Mach-Zehnder Interferometer



[NASA, http:\\www.nasa.gov\vision\universe\starsgalaxies\collide_whitedwarf.html]

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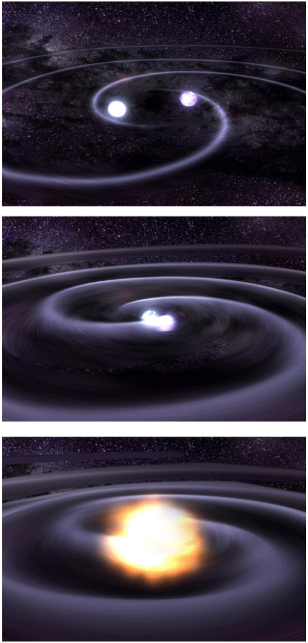

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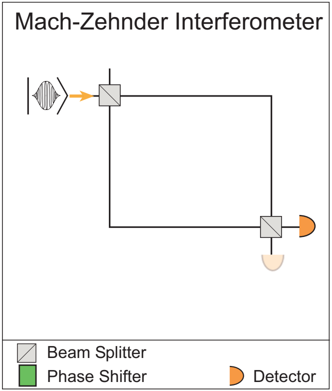

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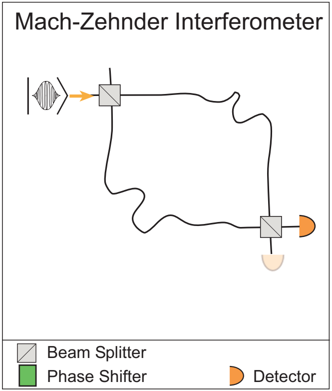

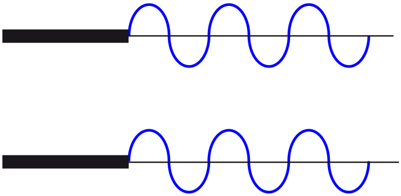

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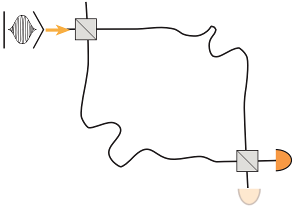
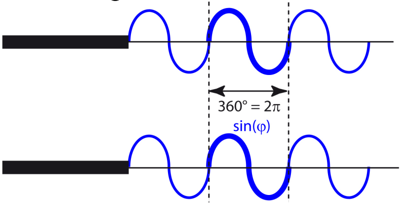


Beam Splitter
Phase Shifter
Detector

No gravitational wave



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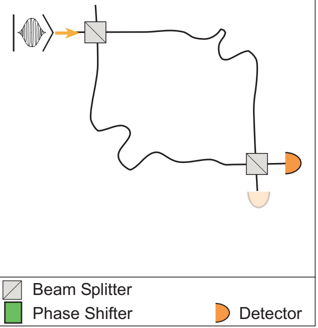

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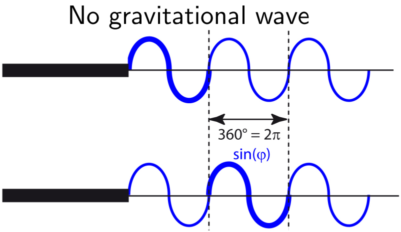

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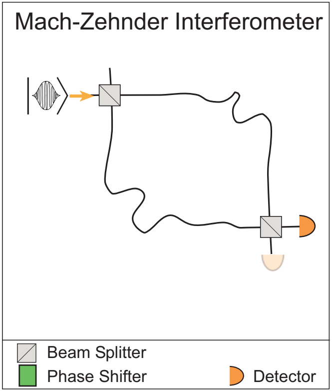

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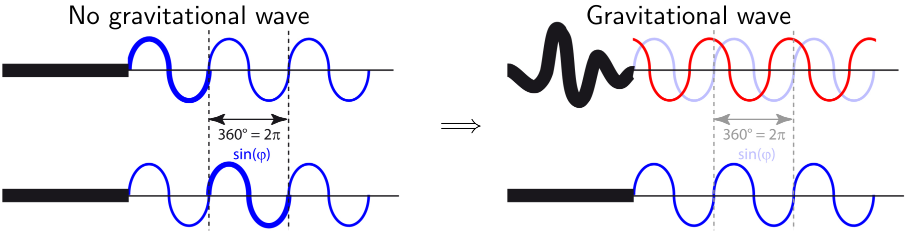

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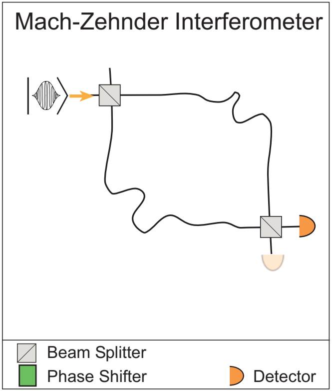

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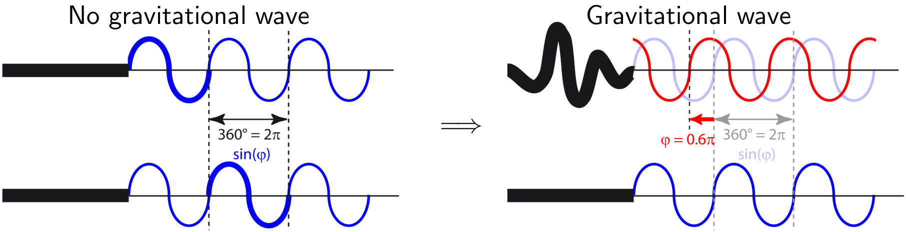

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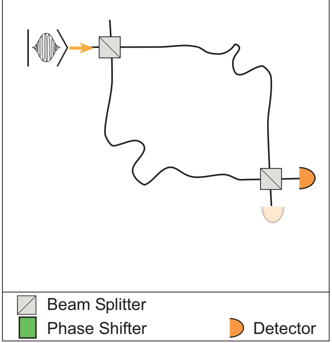

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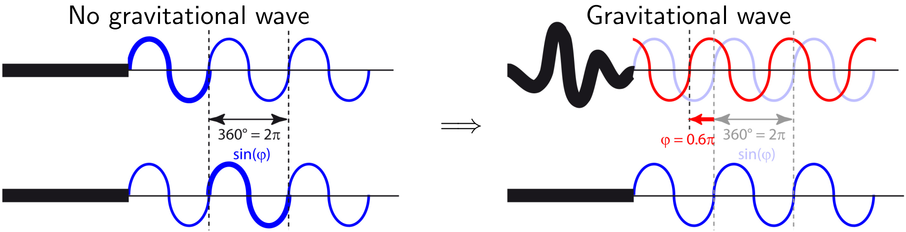

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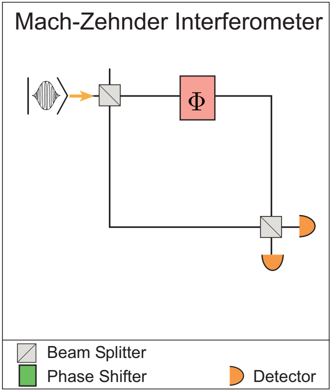

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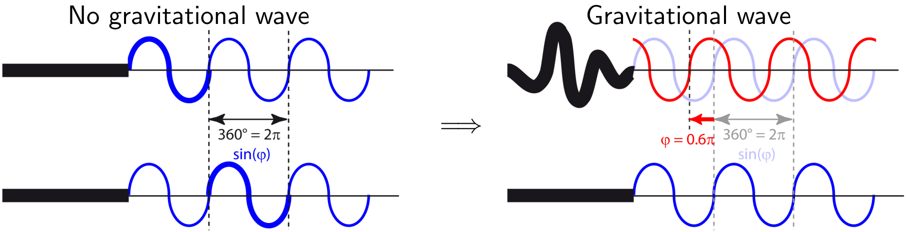

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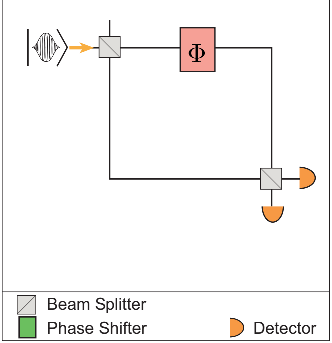

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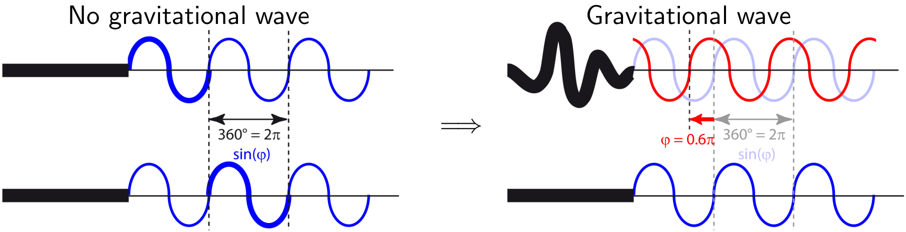

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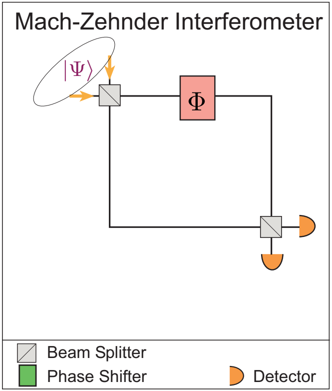

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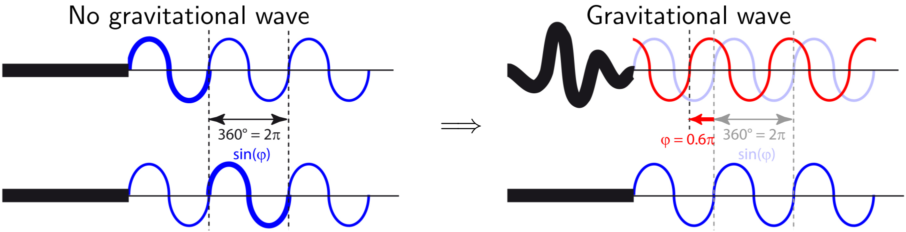

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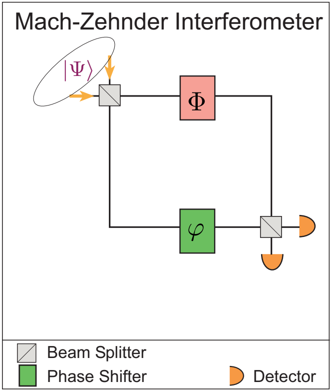

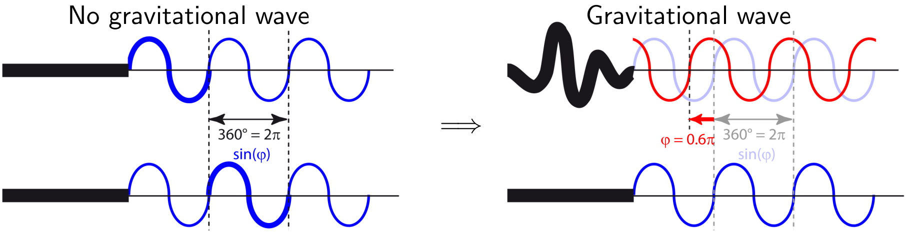

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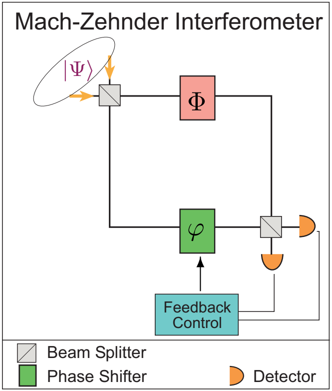


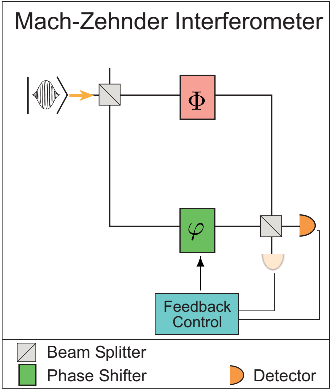
Feedback Algorithms

A simple feedback strategy

- input: N photons in horizontal arm
- tune φ until output: only photons on horizontal arm

Disadvantages:

- bad sensitivity
  $$\Delta\Phi \sim \frac{1}{\sqrt{N}}$$
- to achieve sufficient sensitivity: many photons required $\Leftrightarrow$ measurement slow



Aim: feedback strategy with better sensitivity $\gtrsim \frac{1}{N}$

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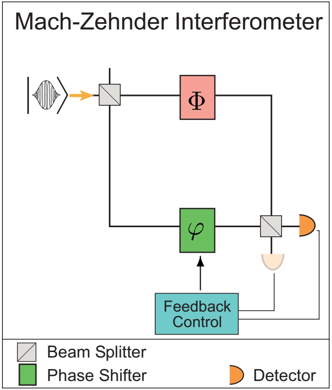

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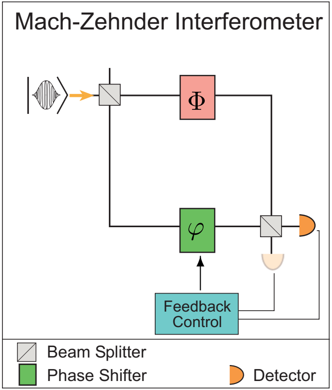

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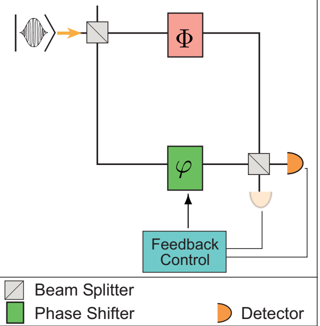

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A simple analogy of the learning problem

Guessing the number Φ rolled on a dice

- unknown parameter: Φ
- player can ask 3 questions $\varphi^{(0)}, \varphi^{(1)}, \varphi^{(2)}$
  response: binary value
- *after* all 3 questions have been answered:
  player gives estimate $\widetilde{\Phi}$ for number rolled

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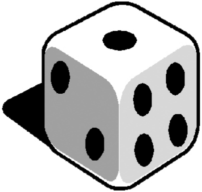

Learning phase: Φ revealed *after game*

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Gravitational Wave Detection

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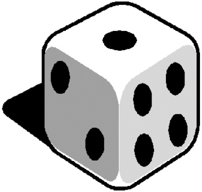

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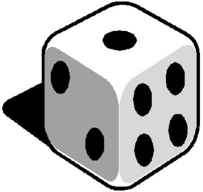

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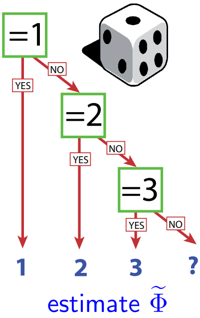

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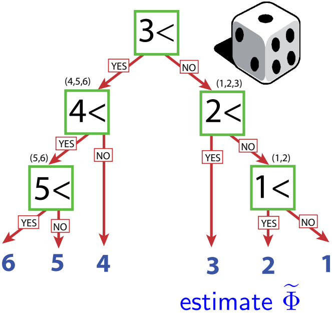

Learning phase: Φ revealed *after game*

- feedback strategy
- reward gained at end of game

Gravitational Wave Detection

- unknown parameter: $\Phi \in [0, 2\pi]$
- action: choose $\varphi^{(i)} \in [0, 2\pi]$
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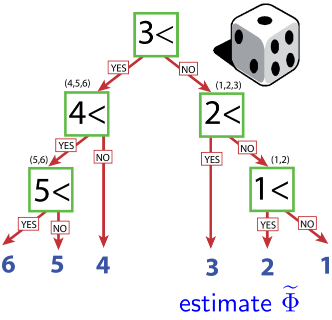

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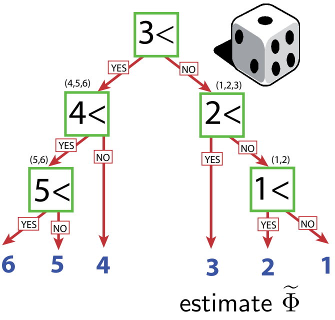

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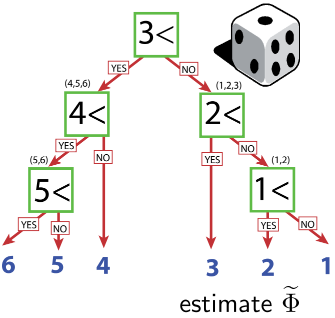

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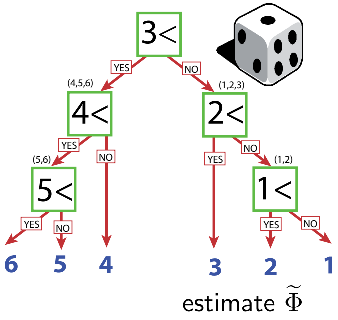

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A high sensitivity feedback strategy

- input: fixed state $|\Psi\rangle$ of
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- no prior information about Φ:
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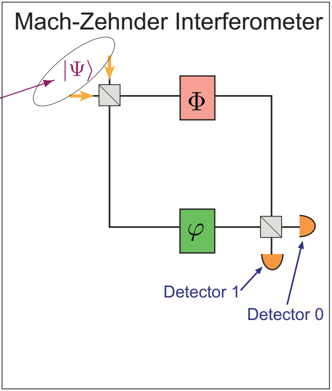
- final phase estimates $\tilde{\Phi}$ determined by measurements



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evaluate fitness of decision tree with Bayes Theorem

vary decision tree using evolutionary algorithm

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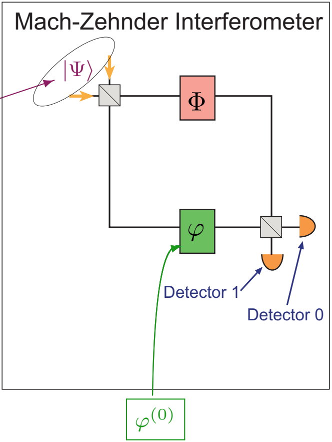

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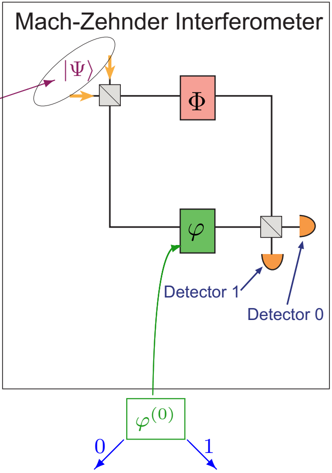

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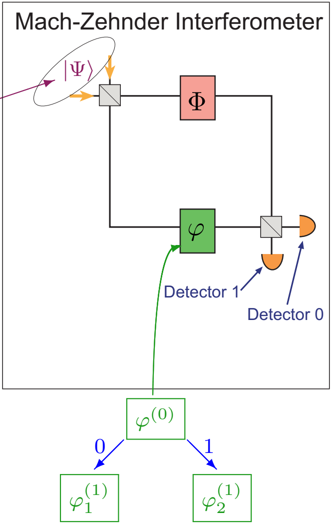

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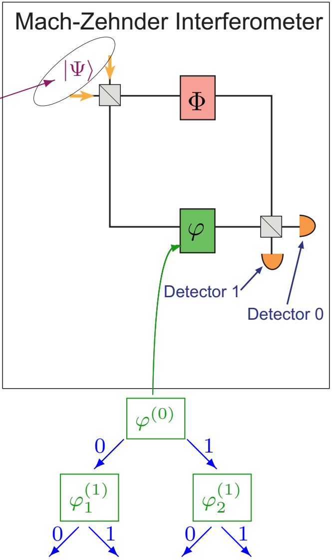

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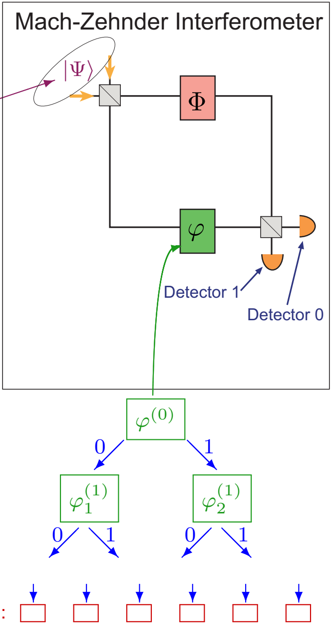

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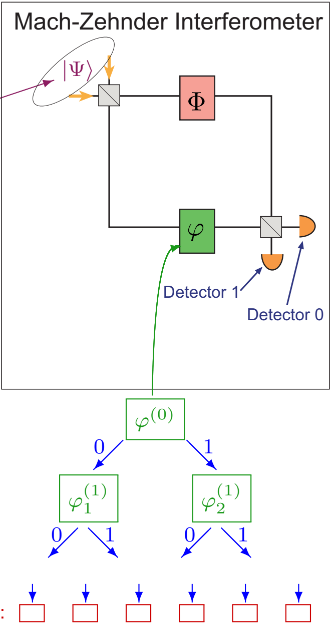

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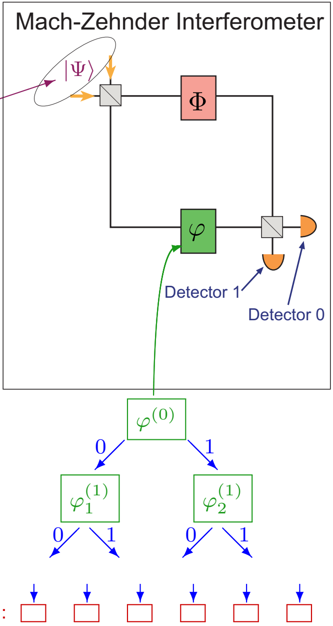

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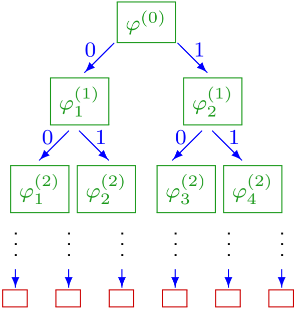
- tree size exponential in number of photons N

highest possible sensitivity $\sim \frac{1}{N}$

- only $\mathcal{P}(N)$ many paths for each $\widetilde{\Phi}$ necessary



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- noise tolerant
  without knowledge of specific noise process
- works for any prior distribution of phase Φ
- different input states $|\Psi\rangle$ possible
- potential to do better than other measurement schemes (depending on training)
- experimentally feasible

Future work:

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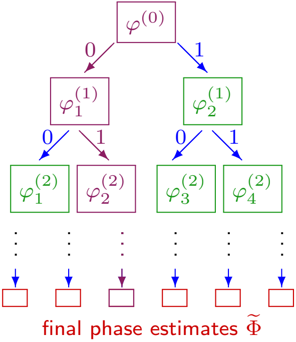

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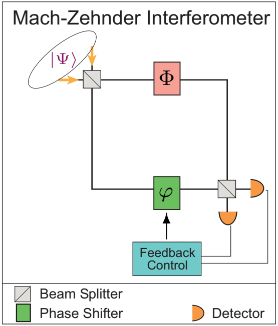

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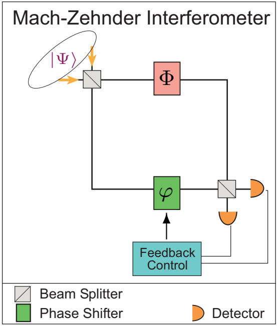

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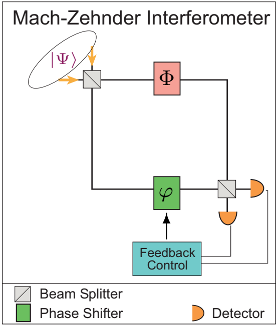

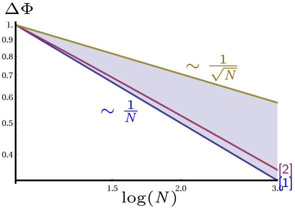

[1] B. Sanders, G. Milburn, Z. Zhang, Journal Mod. Opt. 44, 1309 (1997)

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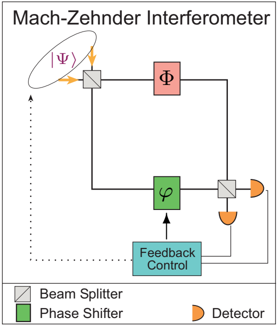

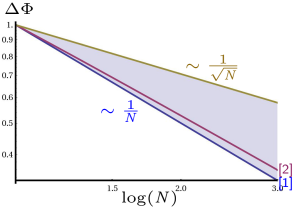

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- Efficient factorization
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  [Algorithm by Peter Shor, 1994]

- Searching an *unsorted* list
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- Simulation of quantum system
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- No efficient algorithm for factorization known

- Search for element in unstructured database:
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- far from possible:
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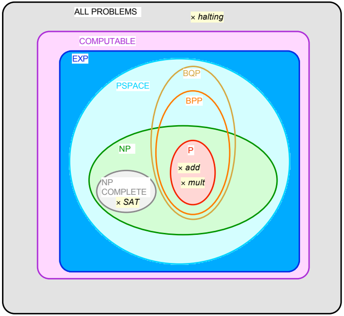

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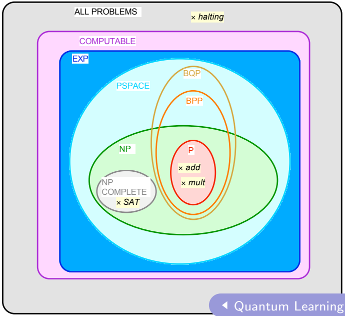

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Quantum Learning