Spin Wave Logic Circuits: Progress Update

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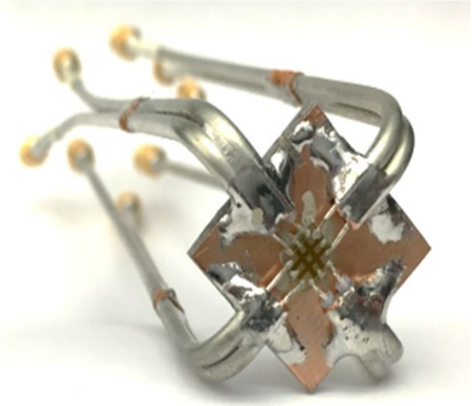
Quantum Computing without Quantum Computers: Database Search and Data Processing Using Classical Wave Superposition by M. Balinskiy et al, in press, (2021)**. https://arxiv.org/abs/2012.08401**

OUTLINE



1. Introduction
2. Oracle Classic (Oracle-C)
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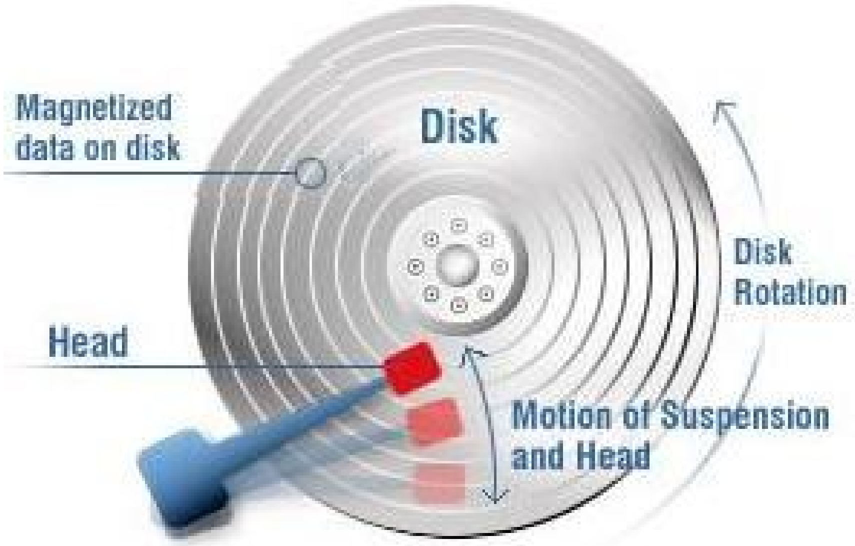
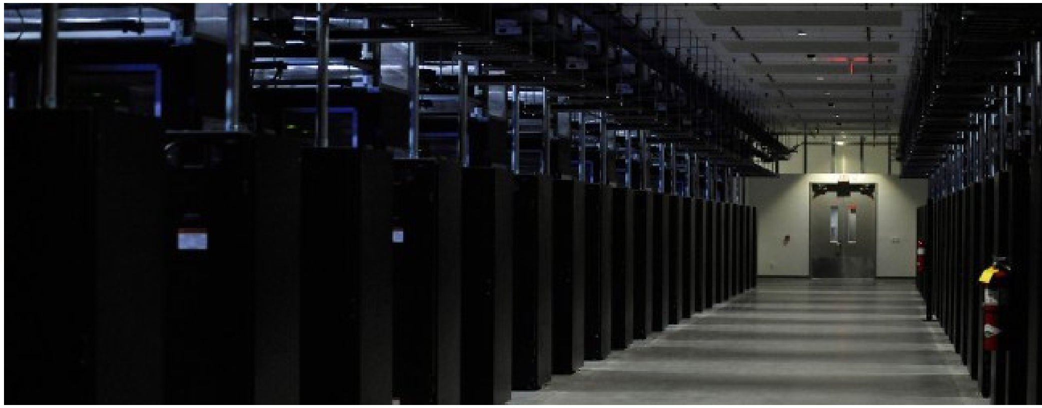
1. Introduction

Magnetic Hard Disk



Google Database Server



http://www.newscientist.com/article/mg22329832.700-googles-factchecking-bots-build-vast-knowledge-bank.html

Magnetic memory is a very efficient data storage technology

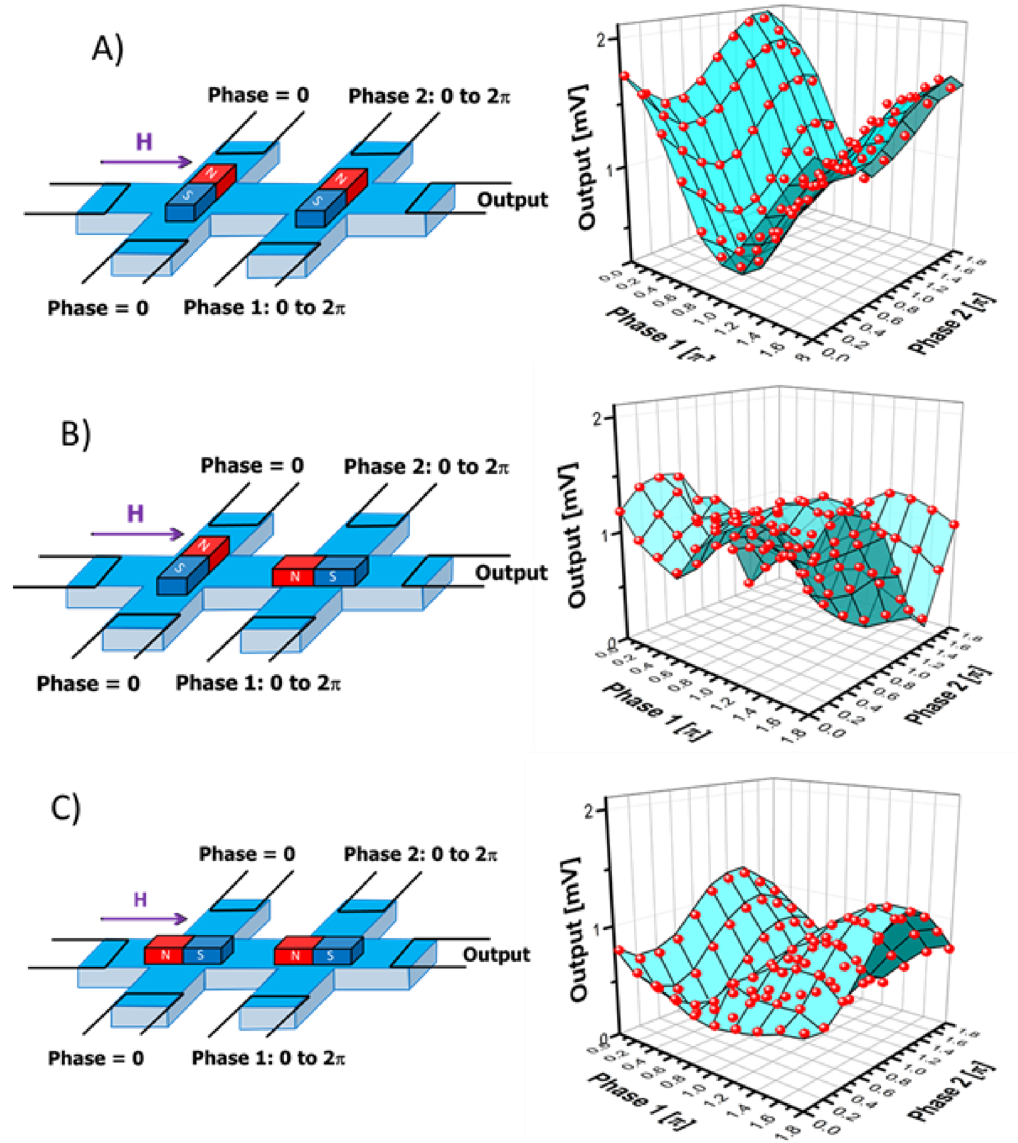
But,

Sequential access: one bit at the time

Magnonic Holographic Memory (MHM)

MHM prototype: double-cross YIG structure with micro-magnets placed on the top of the junctions

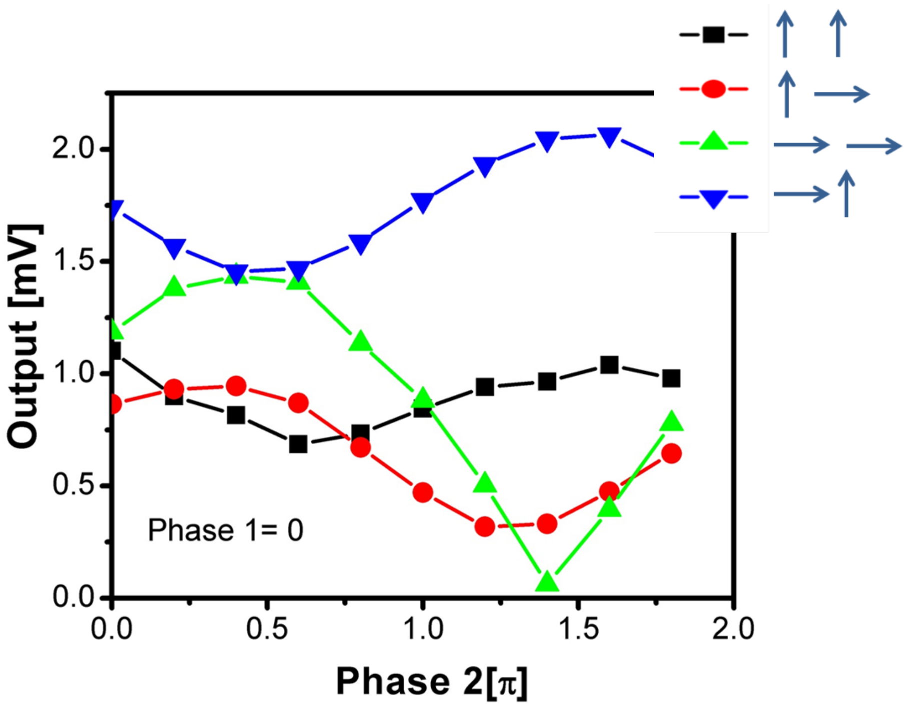
- Information is stored in the magnetic states (e.g. 0 and 1 correspond to the two directions of magnetization)
- Spin wave propagating in YIG are affected by the magnetic field produced by the magnets
- Output voltage is the result of spin wave interference allowing us to reconstruct the magnetic memory states
- Each of the 4 possible combinations has a unique interference signature

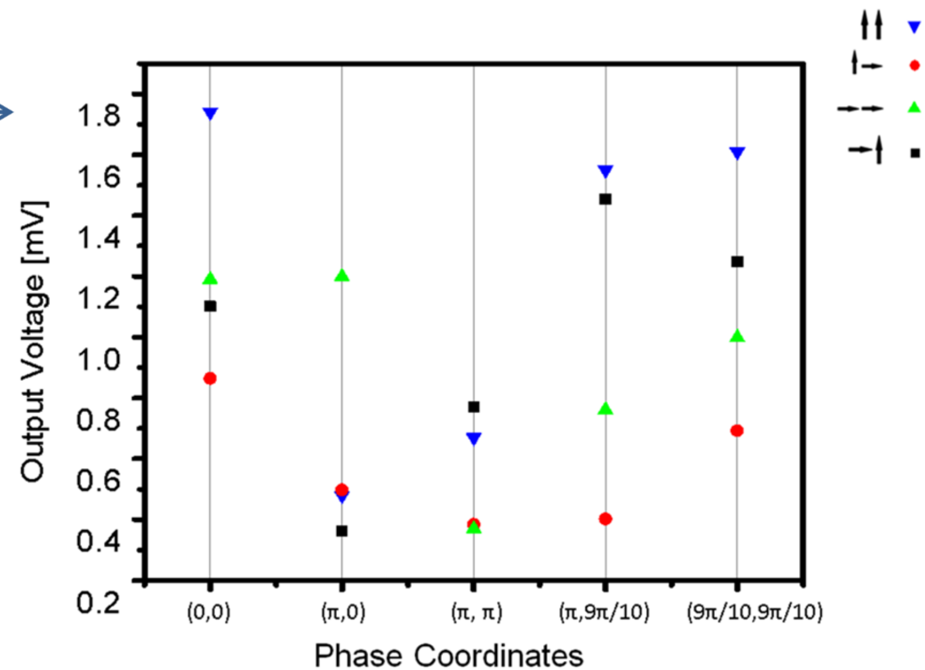


The first 2-bit prototype operates at 5.2GHz. All experiments are done at room temperature.

F. Gertz, A. Kozhevnikov, Y. Filimonov, and A. Khitun, Magnetics, IEEE Transactions on (99) (2014).

Magnetic Memory Read-Out



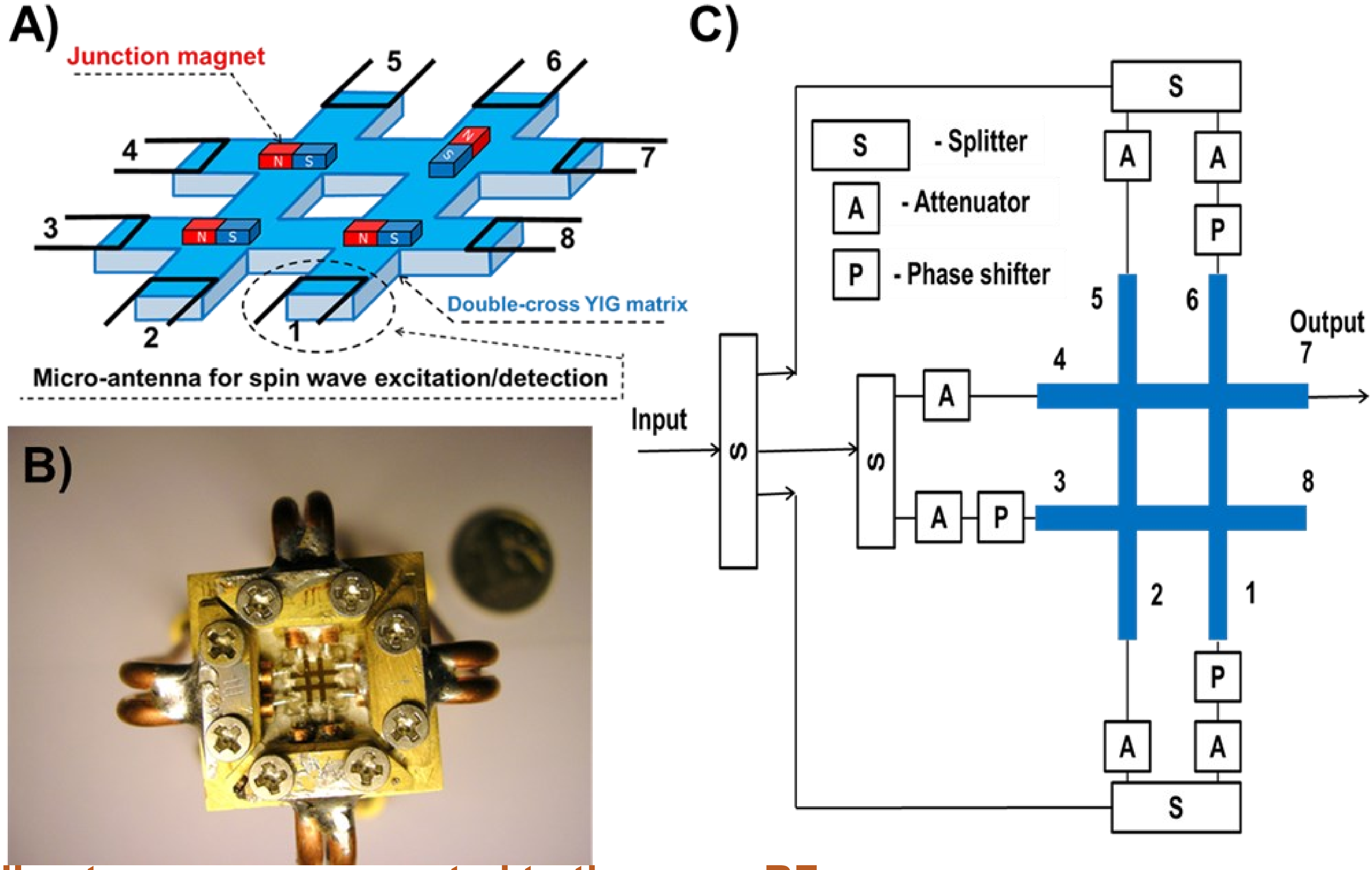


The graphs show the unique holographic signature of the magnetic structure with two magnets placed on the top of the junctions. The graph on the left shows the output in mV as a function of the spin wave phase 2 (the connection schematics are shown on the previous slide). The output oscillates with the phase difference as predicted by numerical simulations.
The graph on the right shows the output in mV for some certain combinations of input phases (phase 1 and phase 2). Each of the four states of the magnets *can be recognized just with one measurement*.
The recognition for bigger magnetic matrixes (*n*×*n* junctions) can be done in a similar way in one step by measuring the output voltages at *n* output nodes.

F. Gertz, A. Kozhevnikov, Y. Filimonov, and A. Khitun, Magnetics, IEEE Transactions on (99) (2014).

8 - terminal MHM Prototype

8-terminal YIG-based MHM device

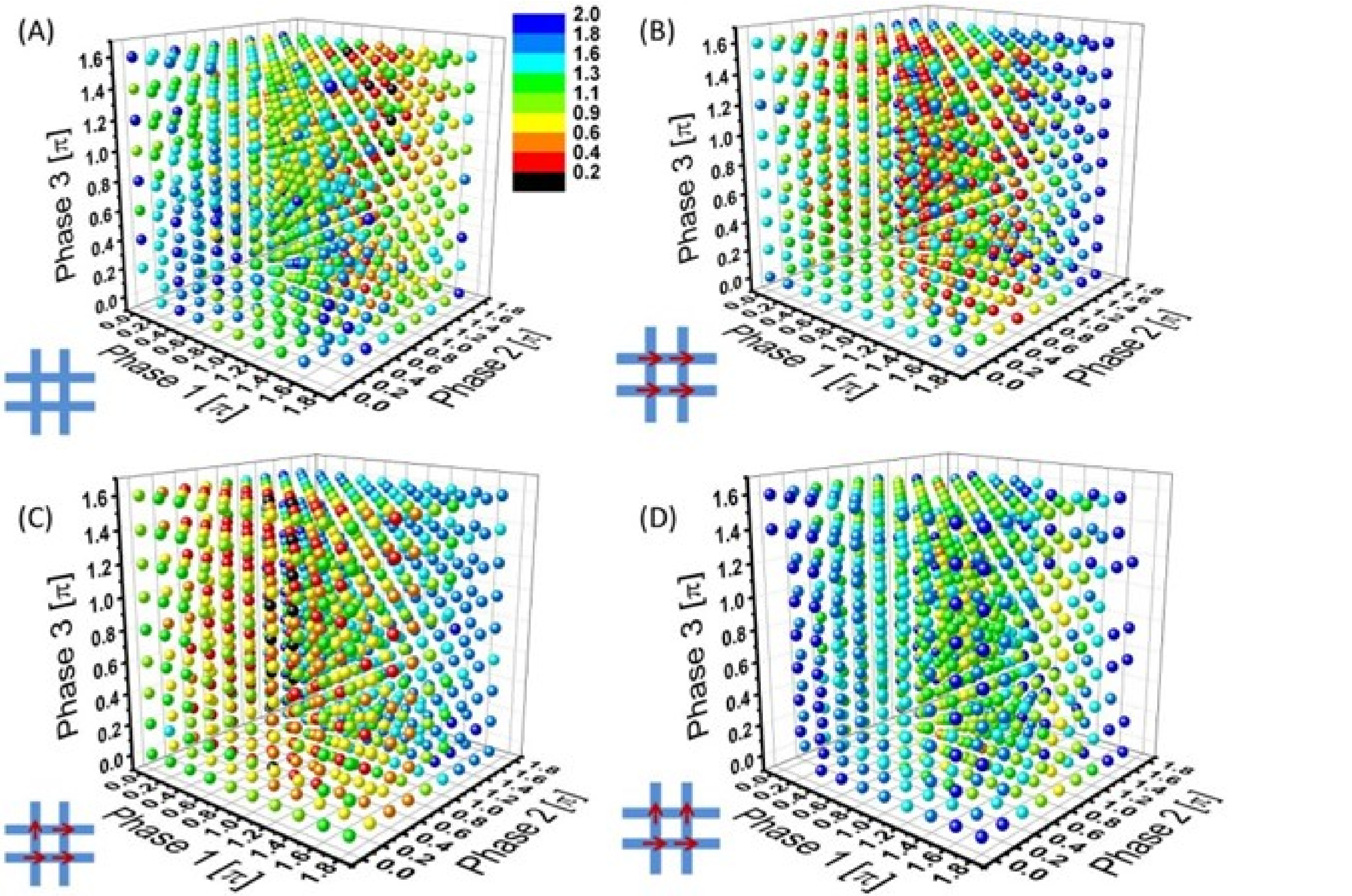


- All antennas are connected to the same RF source
- The phase shift between the ports is controlled by the system of phase shifters

Pattern recognition with magnonic holographic memory device, Kozhevnikov, A.; Gertz, F.; Dudko, G.; Filimonov Yu, and Khitun A. APPLIED PHYSICS LETTERS Volume: 106 Issue: 14 Article Number: 142409, 2015

MHM: Input / Output Correlations

Experimental Data: Magnonic Holograms for different configurations of the junction magnets

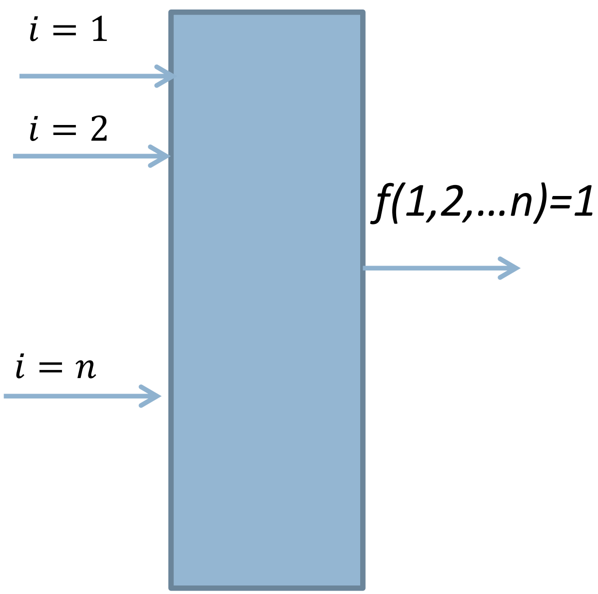


- **The color of the marker correspond to the level of the output inductive voltage**

Pattern recognition with magnonic holographic memory device, Kozhevnikov, A.; Gertz, F.; Dudko, G.; Filimonov Yu, and Khitun A. APPLIED PHYSICS LETTERS Volume: 106 Issue: 14 Article Number: 142409, 2015

Unsorted Database Search

- Quantum computers can search an "unsorted database" (that is, for $f(x): \{0, N\} \rightarrow \{0,1\}$, find x_0 such that $f(x_0) = 1$)in time $O(\sqrt{N})$, compared with the $O(N)$ time that would be required classically



Search Problem

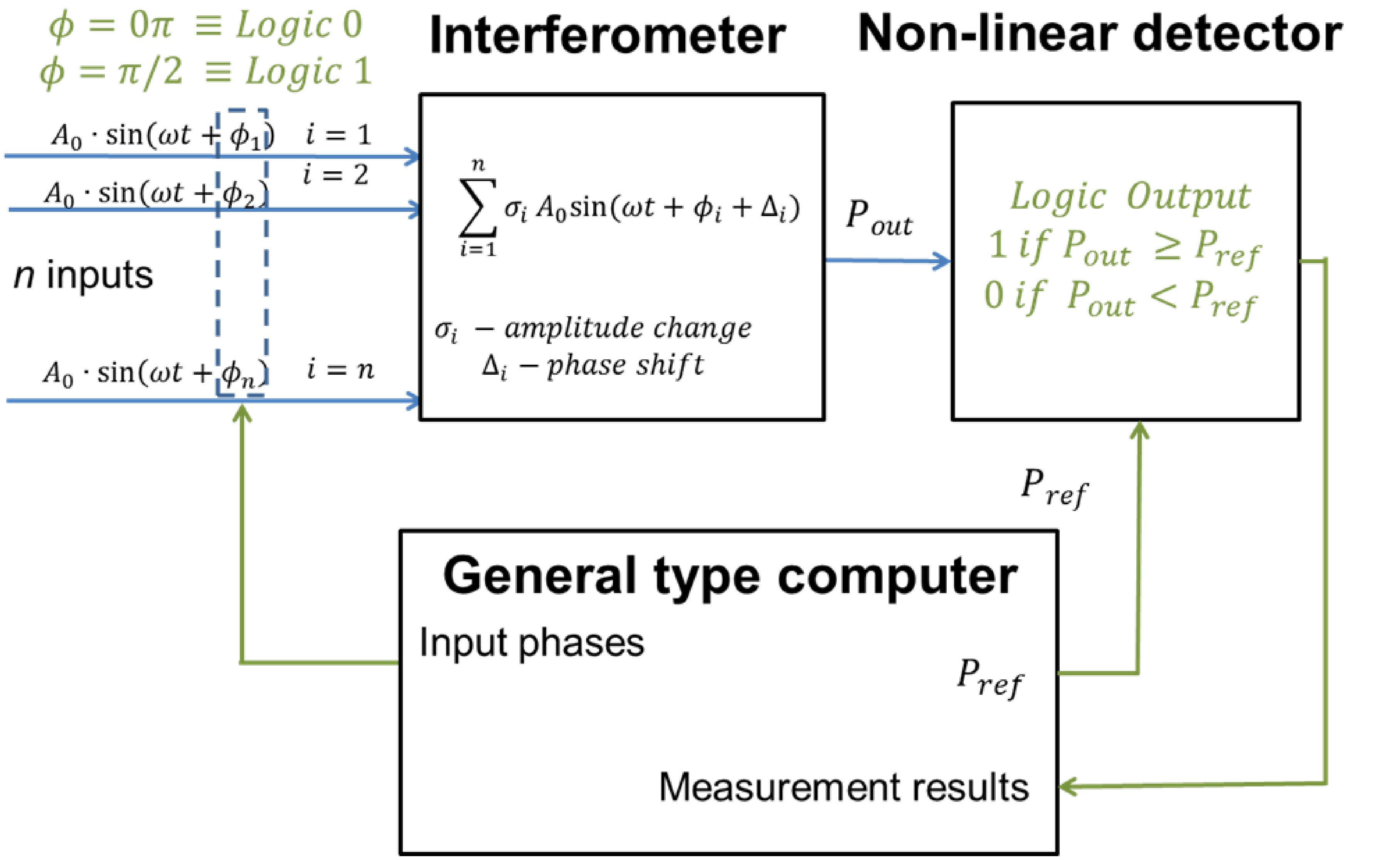
INPUT: $f:\{0,1\}^n \rightarrow \{0,1\}$
PROMISE: $f(a)=1 \quad f(x \neq a)=0$
OUTPUT: binary string a

Classical Complexity: $\Omega(2^n)$

Searching large and unsorted database containing 2^n items

- Example of a sorted database:
  - a phone book if you are given a name and looking for a telephone number
  - n lookups suffice
- Example of an unsorted database:
  - a phone book if you are given a number and looking for a name
  - you need to check 2^n items before you succeed with probability P=1
  - you need to check 2^{n-1} items before you succeed with probability P=0.5

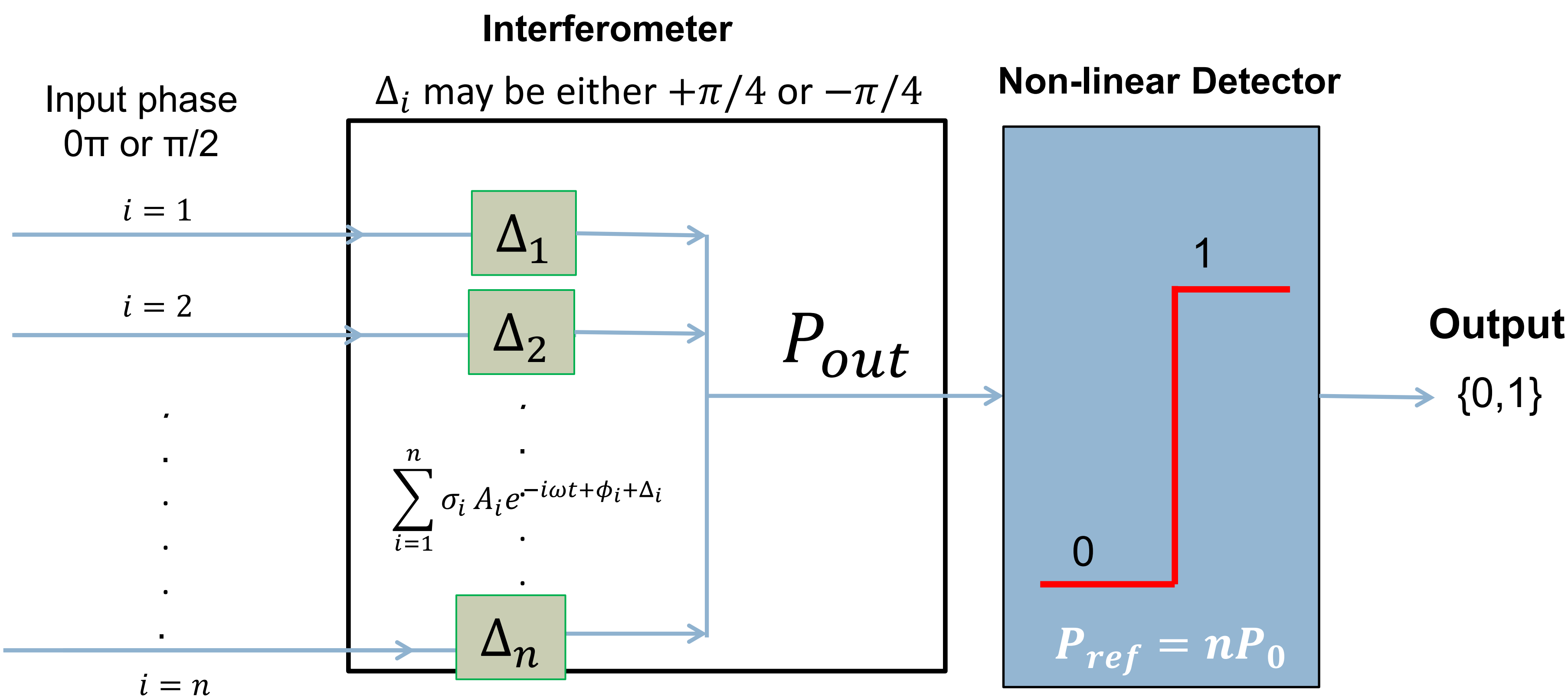
Oracle - C



$\phi = 0\pi \equiv Logic\ 0$
$\phi = \pi/2 \equiv Logic\ 1$
Interferometer
Non-linear detector
$A_0 \cdot \sin(\omega t + \phi_1)$ $i = 1$
$i = 2$
$A_0 \cdot \sin(\omega t + \phi_2)$
n inputs
$A_0 \cdot \sin(\omega t + \phi_n)$ $i = n$
$\sum_{i=1}^{n} \sigma_i A_0 \sin(\omega t + \phi_i + \Delta_i)$
σ_i – amplitude change
Δ_i – phase shift
P_{out}
Logic Output
$1\ if\ P_{out} \geq P_{ref}$
$0\ if\ P_{out} < P_{ref}$
P_{ref}
General type computer
Input phases
P_{ref}
Measurement results

Example 1: unsorted database

Task is to find the only input combination leading to the output 1



There are 2^n possible phase combinations. There are 2^n ways to choose a set of Δ_i. However, there are $2^n - 2$ shifter combinations leading to the only one constructive interference output. Two combinations with all $\Delta_i = +\pi/4 \ \ or \ -\pi/4$ should be excluded from consideration. The reference value in the detector is setup to $P_{ref} = nP_0$, where P_0 is the power provided by just one input. Thus, there is *only one input phase* combination which results in the constructive wave interference providing logic output 1 for the given set of Δ_i.

Algorithmic Pseudocode

- Set all input phases to $\pi/4$
- Start with input $i = 1$
- Consider two possible phases: 0π and $\pi/2$
- Measure P_{ref} – output power for phase combination

$\left\{0\pi, \frac{\pi}{4}, \ldots \frac{\pi}{4}\right\}$

- Measure P_{out} – output power for phase combination

$\left\{\frac{\pi}{2}, \frac{\pi}{4}, \ldots \frac{\pi}{4}\right\}$

- $Phase\ (i) = 0$ if $P_{ref} > P_{out}$

Continue for all remaining inputs $i = 2, n$

Example 1: illustration

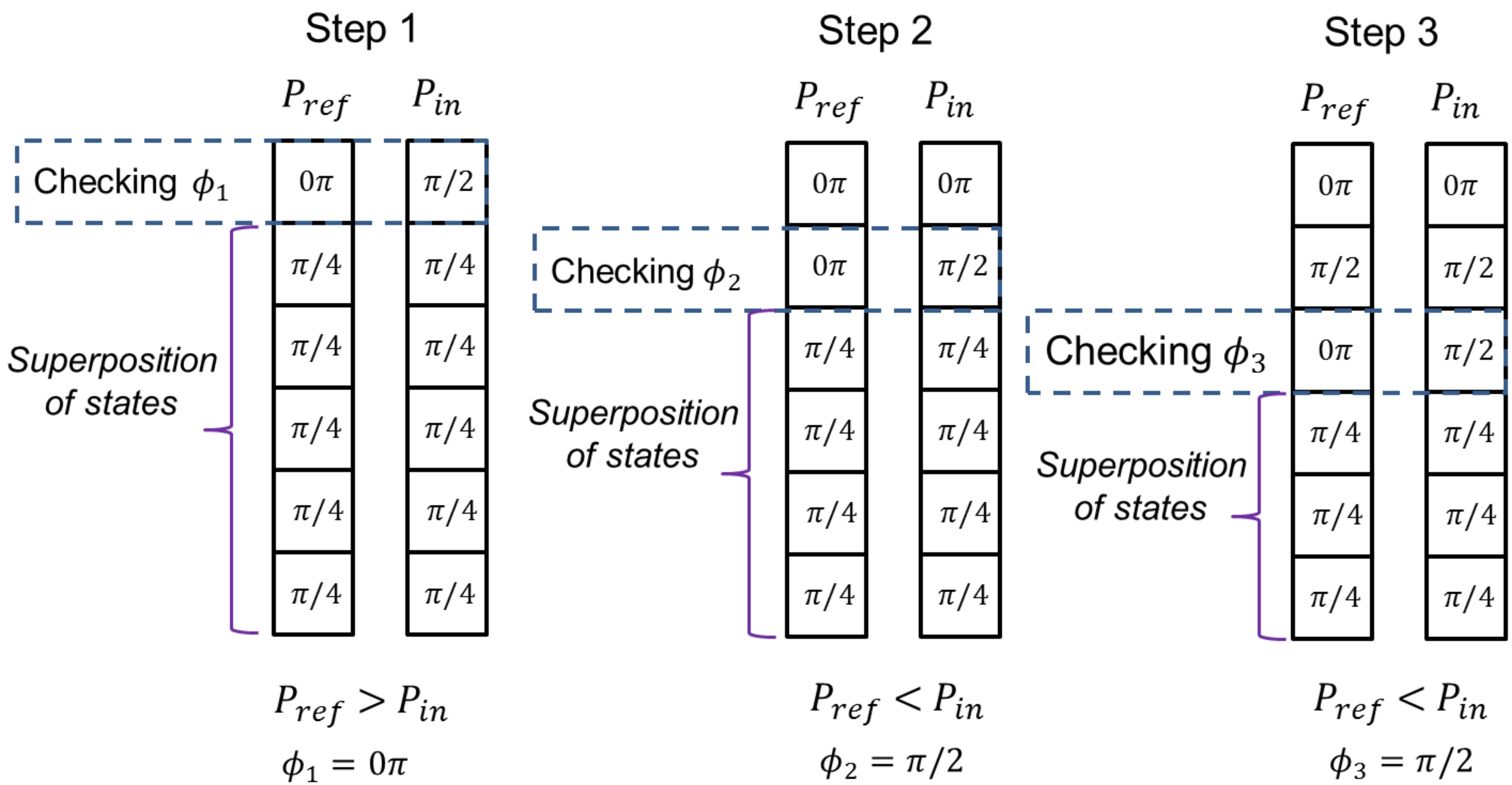
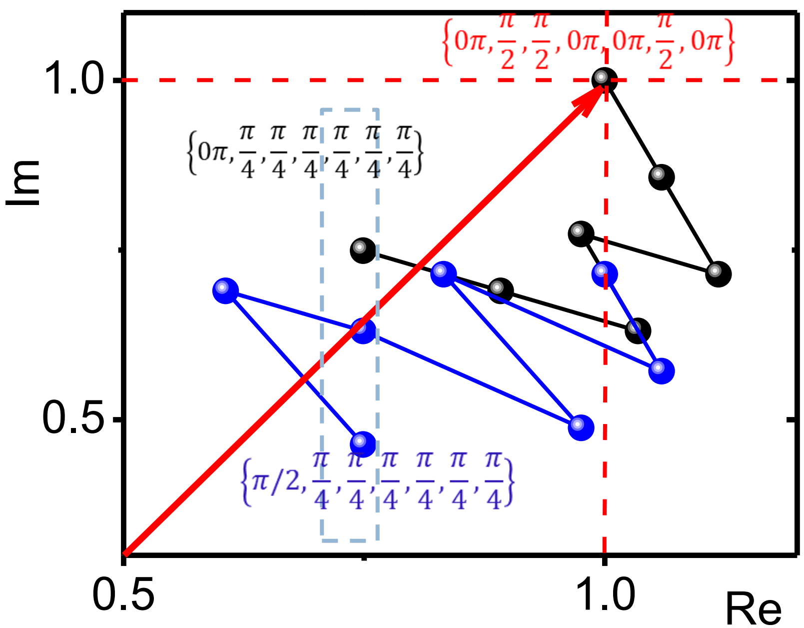
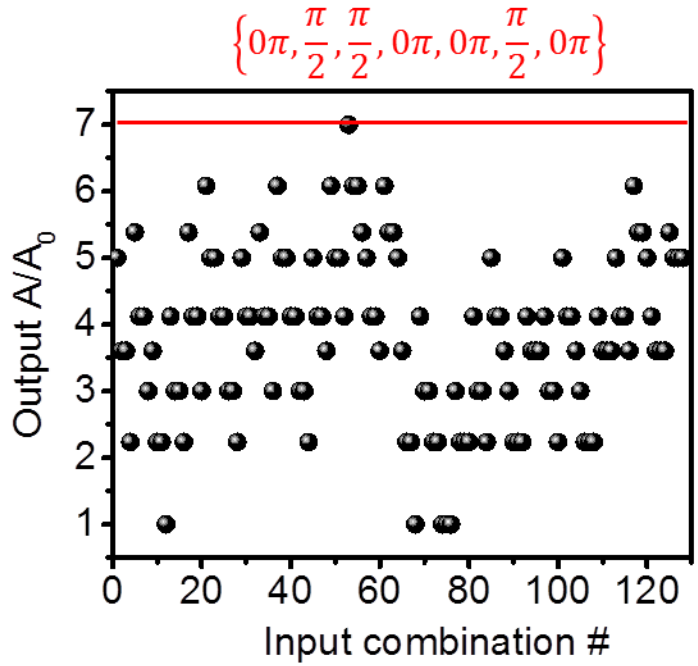


Illustration of the search procedure. There are shown the first three consecutive steps. At the first step all inputs from 2 to *n* are put into a superposition of states. There are two measurements to determine the “true” value of input 1. One measurement is 0> + superposition the other is 1> + superposition. The “true” input always provide the larger output power. It takes *n* steps with *2n* measurements to find the one of the 2^n possible input combinations.

Example 1: numerical modeling





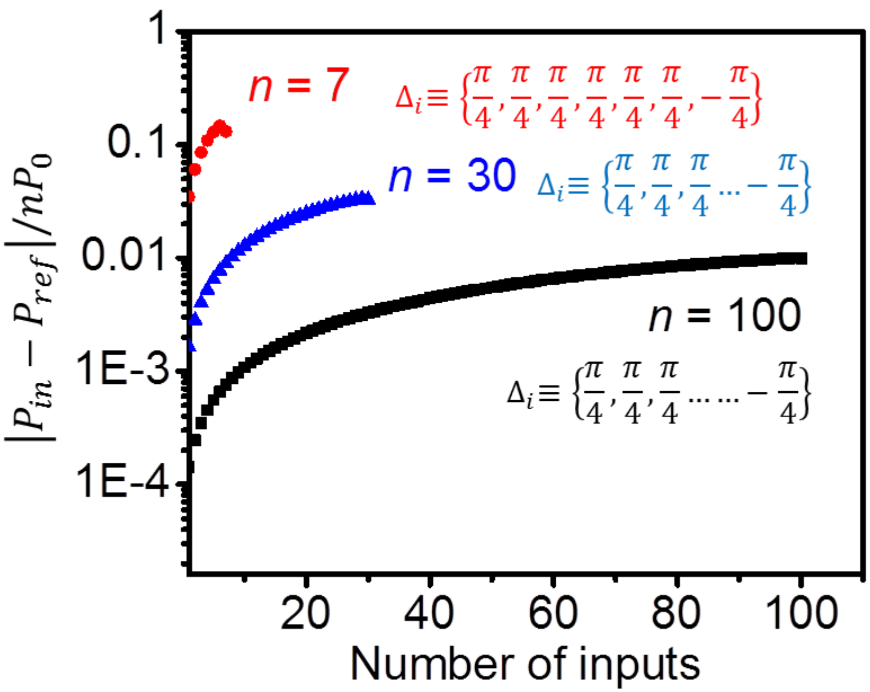
$$y_{out} = A_m \cdot \sin(\omega t + \phi_{out})$$
$$\mathrm{Re}\,(y_{out}) = A_m \cos(\phi_{out})$$
$$\mathrm{Im}\,(y_{out}) = A_m \sin(\phi_{out})$$

$$\Delta_i\{\pi/4, -\pi/4, -\pi/4, \pi/4, \pi/4\}$$

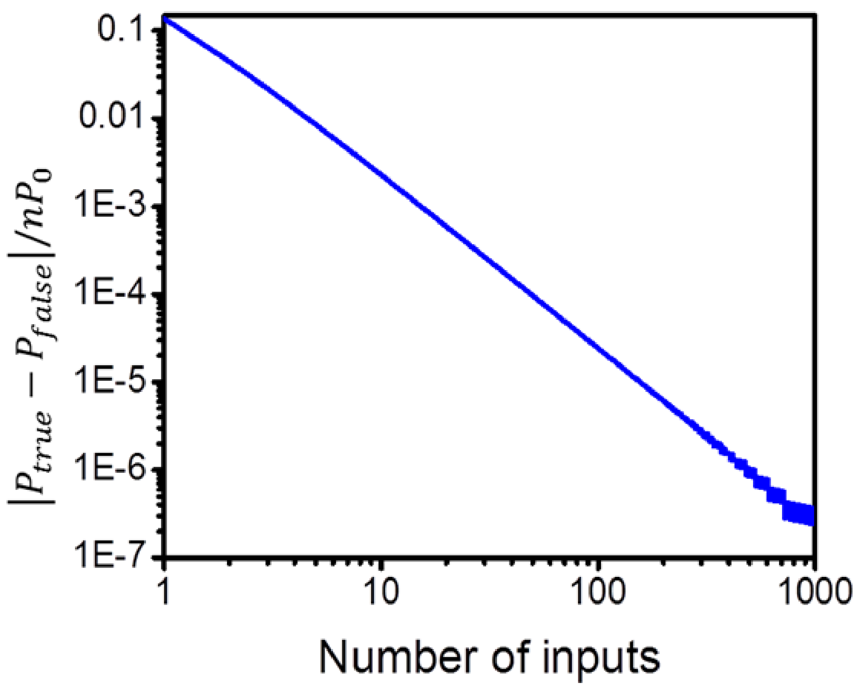
Left: Results of numerical modeling showing the evolution of the evolution of the output signal y_{out} as a vector in a polar form for the seven consequent steps. The black marker corresponds to the "true" phase input while the blue marker corresponds to the "false" input phase. The red vector corresponds to the searched phase combination. **Right:** Results of numerical simulations showing the output amplitude for all possible input phase combinations. The amplitude is normalized to the amplitude of a single input A_0.

Example 1: accuracy of measurements

Accuracy required at each step



Accuracy vs n in the worst scenario



Results of numerical modeling showing the minimum difference between the “true” and the “false” power output. The red, the blue and the black curves correspond to 7-, 30- and 100 input Oracle –C.

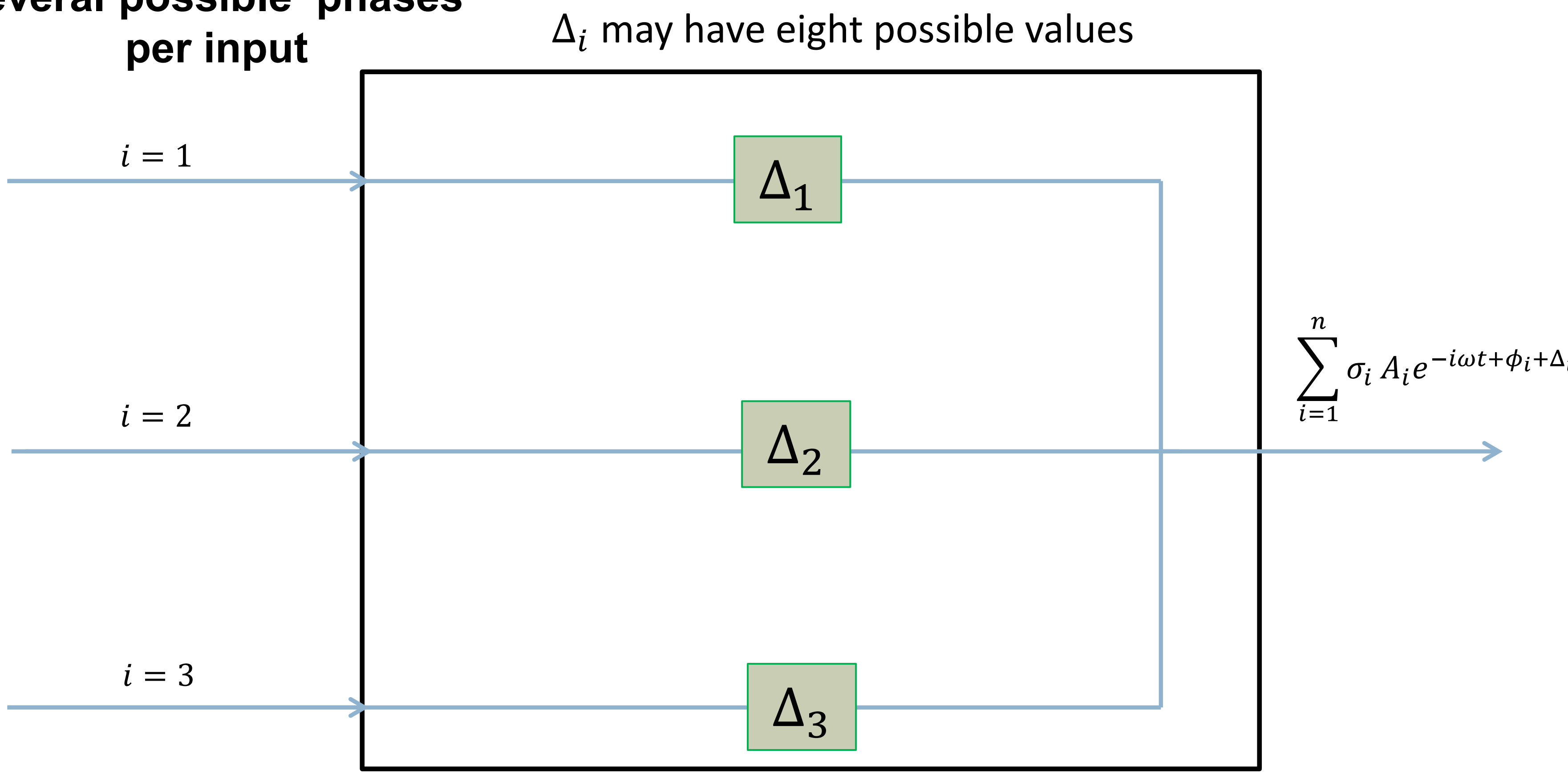
Example 1 : Observations

- It takes 2^n measurements to check all combinations one by one
- It takes $2n$ measurements using state superposition
- The search algorithm was performed for $n = 100$. However, it is not practically possible to verify if this is the only result as it would take 2^{100} operations to check all possible input phase combinations one by one.

Example 2: multi-valued inputs

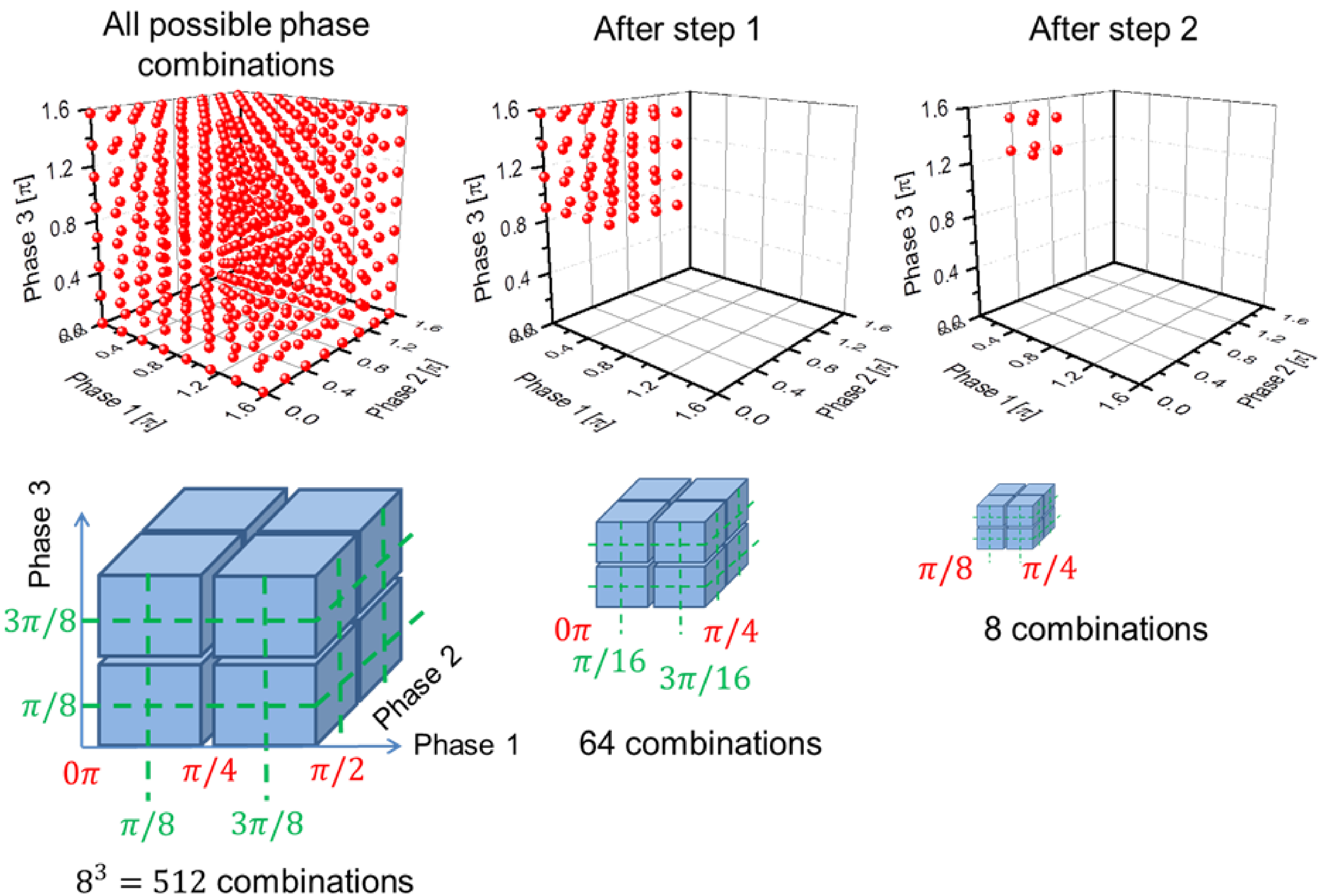
Task is to find the only input combination leading to the output 1

Input: several possible phases per input



Input: possible phases $\left\{0\pi, \frac{\pi}{14}, \frac{2\pi}{14}, \frac{3\pi}{14}, \frac{4\pi}{14}, \frac{5\pi}{14}, \frac{6\pi}{14}, \pi/2\right\}$

Search Procedure



Results of numerical modeling

(A) The results of the first search step

Phase at Input 1 [π]	Phase at Input 2 [π]	Phase at Input 3 [π]	Output amplitude [A_0]
1/8	1/8	1/8	2.38115
1/8	**1/8**	**3/8**	**2.84675**
1/8	3/8	1/8	1.764675
1/8	3/8	3/8	2.35552
3/8	1/8	1/8	2.05607
3/8	1/8	3/8	2.67766
3/8	3/8	1/8	1.65148
3/8	3/8	3/8	2.38115

(B) The results of the second search step

Phase at Input 1 [π]	Phase at Input 2 [π]	Phase at Input 3 [π]	Output amplitude [A_0]
1/16	1/16	5/16	2.84675
1/16	1/16	7/16	2.9405
1/16	3/16	5/16	2.64309
1/16	3/16	7/16	2.78277
3/16	1/16	5/16	2.81112
3/16	**1/16**	**7/16**	**2.95506**
3/16	3/16	5/16	2.65682
3/16	3/16	7/16	2.84675

(C) The results of the third search step

Phase at Input 1 [π]	Phase at Input 2 [π]	Phase at Input 3 [π]	Output amplitude [A_0]
2/14	0	6/14	2.98324
2/14	**0**	**7/14**	**3.0**
2/14	1/14	6/14	2.94986
2/14	1/14	7/14	2.98324
3/14	0	6/14	2.94986
3/14	0	7/14	2.98324
3/14	1/14	6/14	2.93324
3/14	1/14	7/14	2.98324

Phase combination found: $\left\{\frac{\pi}{7}, 0\pi, \frac{\pi}{2}\right\}$

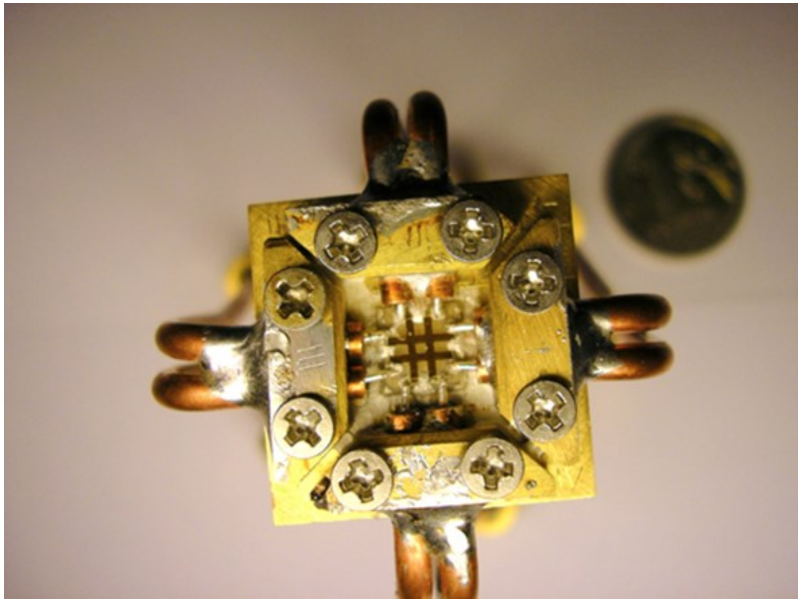
Example 2 : Observations

- One can check that the only one phase combination $\left\{\frac{\pi}{7}, 0\pi, \frac{\pi}{2}\right\}$ provides the constructive output interference for $\left\{\Delta_1 = \frac{5\pi}{14};\ \Delta_2 = \frac{\pi}{2}; \Delta_3 = 0\pi\right\}$
- The search was accomplished in 24 queries. It would take 512 queries on average for a digital computer. In general, the advantage of the superposition technique using phase space division over a classical digital machine is $\mathcal{O}(\sqrt[n]{m})$, where n is the number of inputs (i.e., the dimension of the phase space), and m is the number of states per each input (i.e., the number of phases per input).
- We intentionally take $n = 3$ to have 3D space for all possible phase combinations. Without a loss of generality, $m = 8$ was taken as an example.

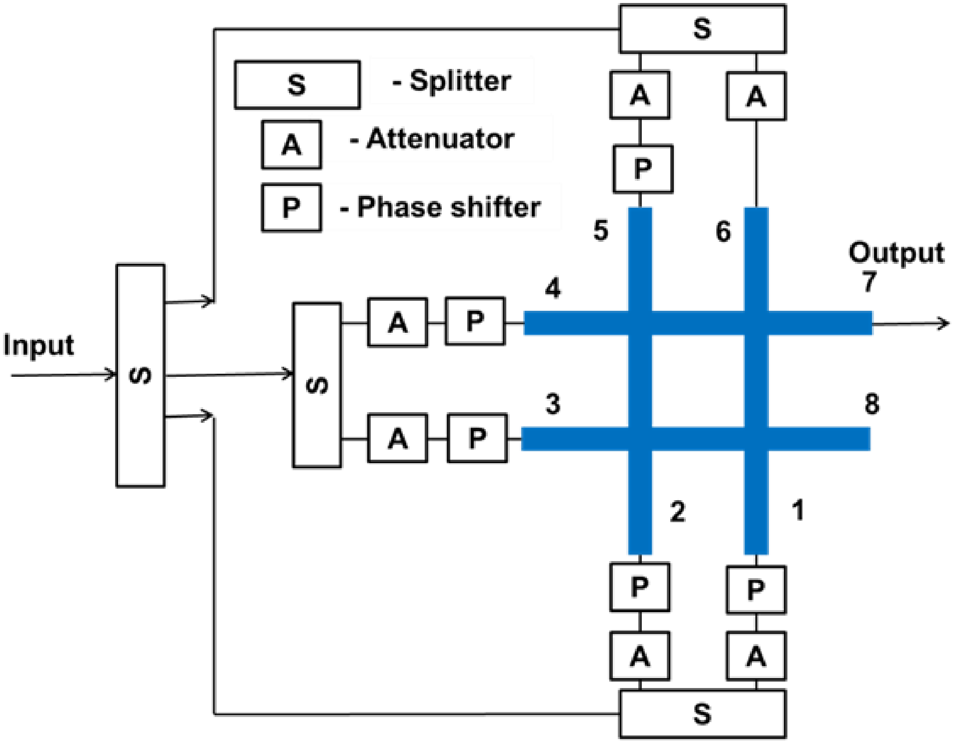
Example 3: Experiment with MHM

Experimental work accomplished on a multi-port spin wave interferometer

Photo of the device



Setup schematics



- All antennas are connected to the same RF source
- The phase shift between the ports is controlled by the system of phase shifters

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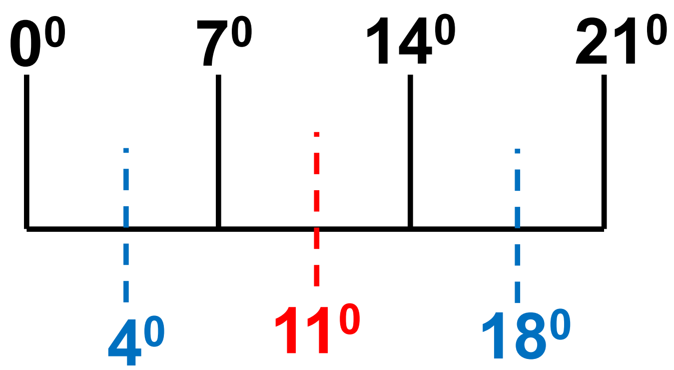
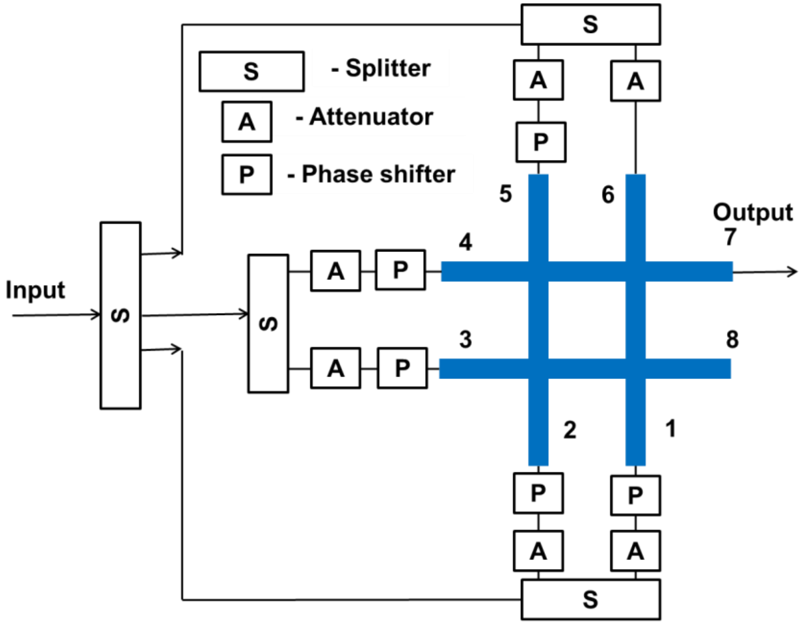
4 phases per input, 5 inputs: 4^5 = 1024 combinations

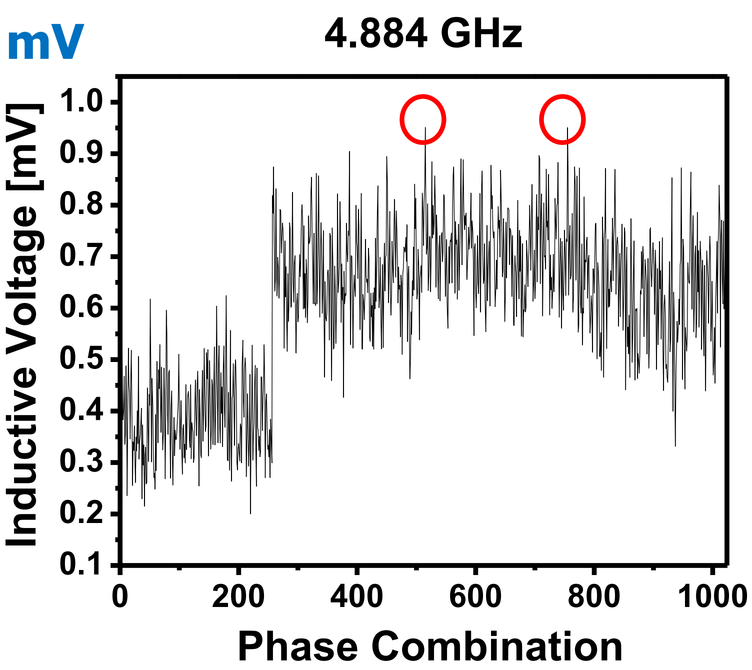
Experiment details:

- There are 5 spin wave generating antennas and one antenna detecting the output inductive voltage
- There are 4 possible phases for each antenna: 0^0, 7^0 , 14^0 , and 21^0. 4^5 =1024 possible phase combinations.
- The phase difference between the waves coming to the output does not exceed π/2
- Input spin wave amplitudes are adjusted by the set of attenuators to provide the same level of the output inductive voltage



Task: find phase combination(s) which provides output inductive voltage ≥ 0.94 mV





Experimental data: Search in 5D space

Step 1: 5D space is divided in $2^5 = 32$ segments, 32 measurements are accomplished We take the segment with the highest output power

Step 2: 32 phase combinations were checked one by one.

Result: There are two phase combinations (21,0,0,0,21) (i.e., # 515 in the graph) and (21,7,7,0,21) (i.e., # 755 in the graph) which provide 0.9501 mV and (0.9507 mV inductive voltage, respectively.

	Classical Computer	MHM - Oracle
Number of queries	**1024**	**64**

The advantage of the superposition technique using phase space division over a classical digital machine is $\mathcal{O}(\sqrt[n]{m})$

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Discussion: Superposition without Entanglement

PHYSICAL REVIEW A, VOLUME 61, 010301(R)

Quantum search without entanglement

Seth Lloyd*

Entanglement of quantum variables is usually thought to be a prerequisite for obtaining quantum speedups of information processing tasks such as searching databases. This paper presents methods for quantum search that give a speedup over classical methods, but that do not require entanglement. These methods rely instead on interference to provide a speedup. Search without entanglement comes at a cost: although they outperform analogous classical devices, the quantum devices that perform the search are not universal quantum computers and require exponentially greater overhead than a quantum computer that operates using entanglement. Quantum search without entanglement is compared to classical search using waves.

To summarize:

(i) A classical digital computer that searches a database with n slots requires $O(\log_2 n)$ resources and has to look at the database $O(n)$ times.

(ii) A quantum digital computer that searches a database with n slots requires $O(\log_2 n)$ resources and has to look at the database $O(\sqrt{n})$ times.

(iii) A classical device that determines which of n slots in a box flips a discrete object, such as a coin, requires $O(n)$ resources and has to pass the coin through $O(n)$ times.

(iv) A quantum device that determines which of n slots in a box flips a discrete object, such as a particle, requires $O(n)$ resources and has to pass the particle through $O(\sqrt{n})$ times.

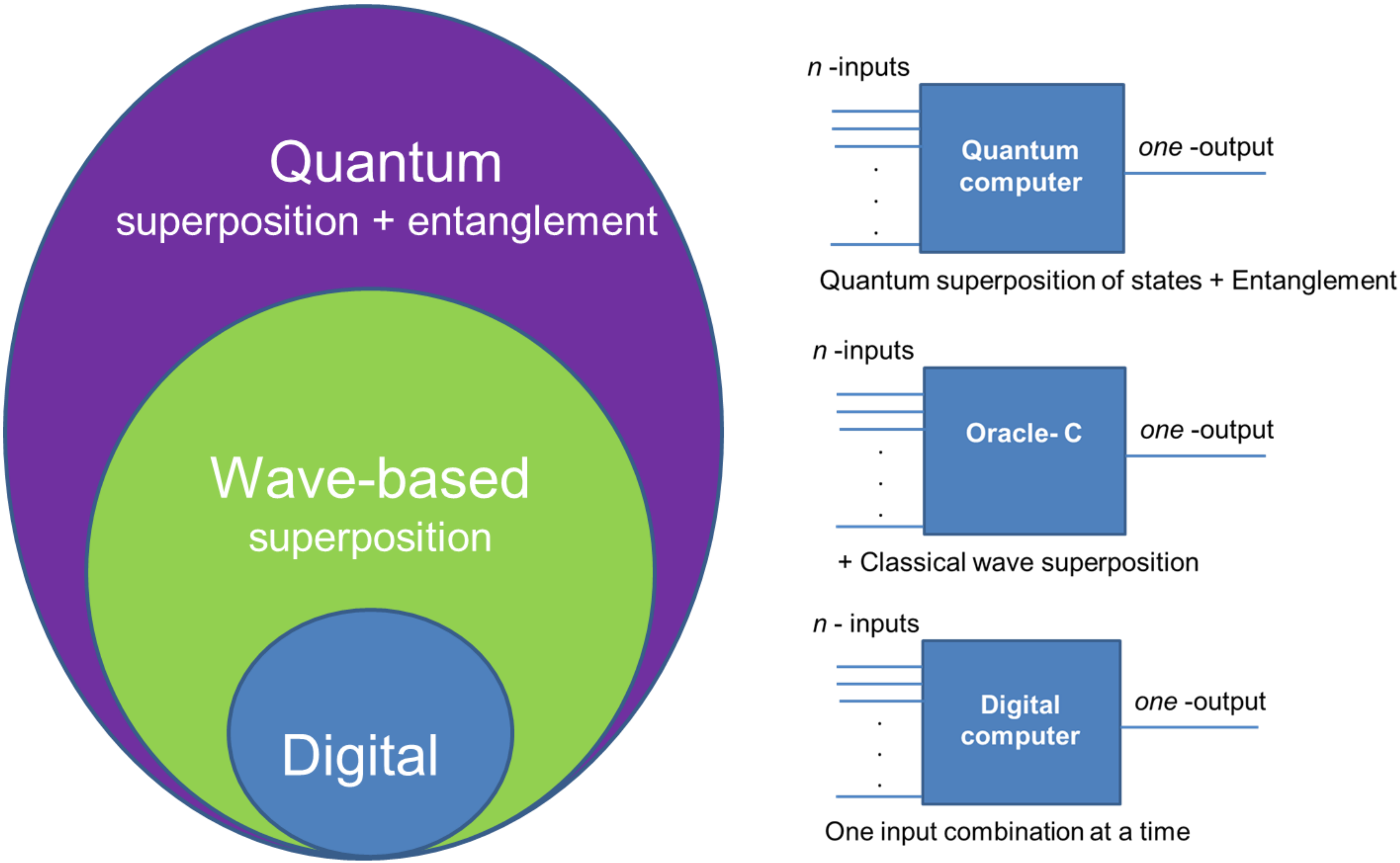
(v) A classical wave device that determines which of n slots in a box flips the polarization of a wave requires $O(n)$ resources and has to send the wave through $O(\sqrt{n})$ times.

We can utilize classical wave superposition without the use of quantum entanglement to speed up data base search

Summary

- Classical wave-based devices may provide a fundamental speedup in database searching compared to classical digital computers.
- Example 1 shows the possibility of finding one of the $2^n - 2$ input combinations in $2n$ steps.
- Examples 2 and 3 demonstrate the feasibility of $\sqrt[z]{m}$ speedup, where z is the dimensionality of the phase space (i.e., the number of independent wave inputs) and m is the number of phases per input.
- The speedup does not come with an exponential resource overhead. Energy and the number of devices scales linearly with the number of inputs n.
- The presented examples are not universal but can be applied to a special type of databases (i.e., with one absolute maximum).
- All of the present examples are based on phase information coding, where logic states are related to the phases of the wave signals. The use of phase possesses certain advantages for parallel data processing (i.e., state superposition).

Computing Power Hierarchy



Quantum Computing without Quantum Computers: Database Search and Data Processing Using Classical Wave Superposition, M. Balinskiy et al., in press, 2021

THANK YOU FOR YOUR ATTENTION!

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Quantum Computing without Quantum Computers: Database Search and Data Processing Using Classical Wave Superposition by M. Balinskiy et al, in press, (2021)**. https://arxiv.org/abs/2012.08401**