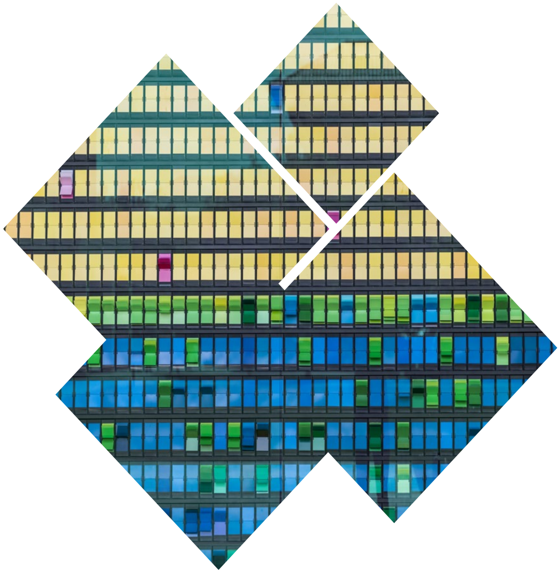
White Paper

Leveraging Physics & Memory
A paradigm shift for Efficient Computing

How memory can be used to create a new class of <u>scalable</u> machines called

Digital Memcomputing Machines

MemComputing Inc.



EXECUTIVE SUMMARY

Physical phenomena may be of great help in computing some difficult problems efficiently. A typical example is prime factorization that may be solved in polynomial time by exploiting quantum entanglement on a quantum computer. There are, however, other types of (non-quantum) physical properties that one may leverage to efficiently compute a wide range of hard problems.

One such property is memory. Our computers, from your cell phone, laptop to the biggest supercomputer, follow the von Neumann architecture. Memory and compute are separate in this architecture. However, taking a wholly new approach, we felt that memory could be used in a novel physics-based approach to computation

Memory + Computing = MemComputing

Digital Memcomputing Machines (DMMs) are **scalable** and can be realized with non-linear dynamical systems with memory. The latter property allows the realization of a new type of Boolean logic, one that is self-organizing. Self-organizing logic gates do not distinguish between the input and output terminals. When appropriately assembled to represent a given combinatorial / optimization problem, **the corresponding self-organizing circuit converges to the equilibrium points that express the solutions of the problem at hand**.

DMMs are robust against noise and structural disorder. Since DMMs are non-quantum systems described by ordinary differential equations, not only can they be built in hardware with the available technology, they can also be simulated efficiently in software on the standard computers that we use today.

1 BOOLEAN ALGEBRA AND LOGIC GATES

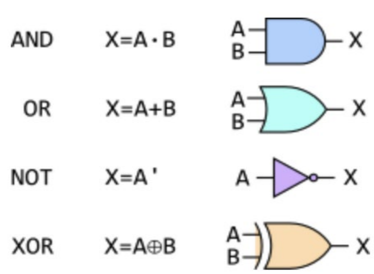
In computing and telecommunications, **binary codes are used for various methods of encoding data**, such as converting character strings into bit strings. Modern computers and digital electronics uses binary logic gates, that basically have two states, on or off (1 or 0), and depending on how you tie them together they'll give you a different state depending on the inputs. This is known as digital logic.

The manipulation of **finite strings of 0s and 1s which are encoded through physical properties,** is represented by low and high current in transistors, magnetization patterns in magnetizable materials, or charges in capacitors.

In the 1840s, English mathematician George Boole developed an algebra (a set of operators and laws) for variables that can have just two states – true and false. Thus, a Boolean value is equivalent to one bit:

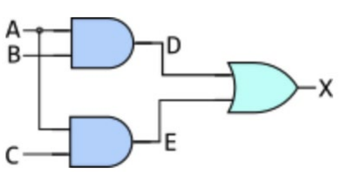
- False = 0 = off
- True = 1 = on

The operators defined by Boole are pervasive throughout all of computing. The behavior of these operators can be defined by truth tables as presented here

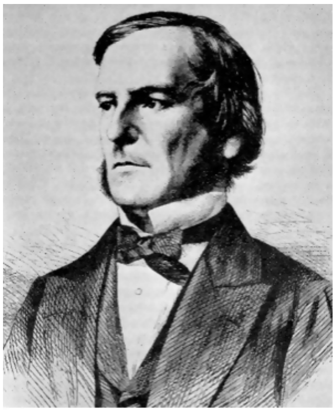


A	B	A·B	A+B	A'	A⊕B
0	0	0	0	1	0
0	1	0	1	1	1
1	0	0	1	0	1
1	1	1	1	0	0

Gates can be combined into combinational circuits to achieve various effects. For example, the algebraic expression X = A·B + A·C corresponds precisely to the following circuit diagram:



A	B	C	D=A·B	E=A·C	X=D+E
0	0	0	0	0	0
0	0	1	0	0	0
0	1	0	0	0	0
0	1	1	0	0	0
1	0	0	0	0	0
1	0	1	0	1	1
1	1	0	1	0	1
1	1	1	1	1	1



George Boole
(1815-1864)

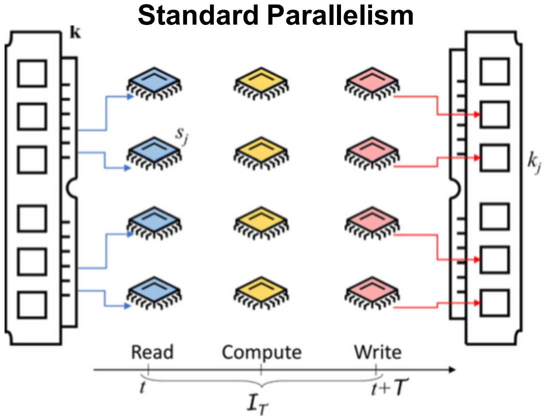
2 DIGITAL MEMCOMPUTING MACHINES (1/2)

Key Characteristics of Digital Memcomputing Machines (DMMs)

- **DMMs can be realized in practice by designing appropriate (non-quantum) non- linear dynamical systems.**
  - These dynamical systems have internal degrees of freedom (memory, hence the name mem-computing).
  - This allows us to engineer a new type of Boolean logic that is terminal-agnostic, namely, one that does not distinguish between the input and output. In other words, each terminal is input and output.
  - Therefore, while maintaining the digital structure of the input and the output (hence requiring finite means to read/ write the output/input), DMMs built out of these new types of gates can self-organize, collectively, to solve very complex problems very efficiently.
  - DMMs perform computation embedded in memory, employing all of their fundamental units, at once
- **DMMs allow us to reap great benefits from just simulating them on our traditional computers**
  - DMMs are non-quantum devices
  - Their equations of motion can be simulated efficiently on our modern computers, delivering substantial advantages compared to standard algorithms for a wide range of problems of combinatorial/optimization.
  - DMMs do not require more than standard Complementary Metal Oxide Semiconductor (CMOS) technology to be built in hardware if emulators of circuit elements with memory are employed

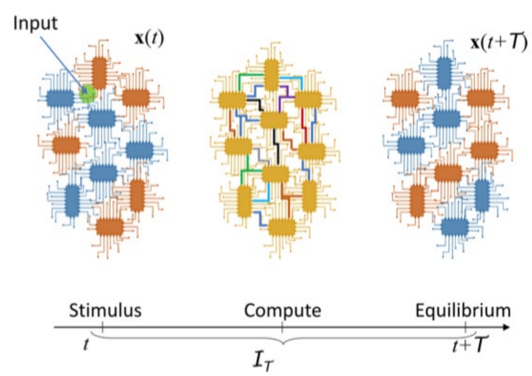
A new logic Framework: Self-Organizing Logic Gates (SOLGs)

Standard Parallelism



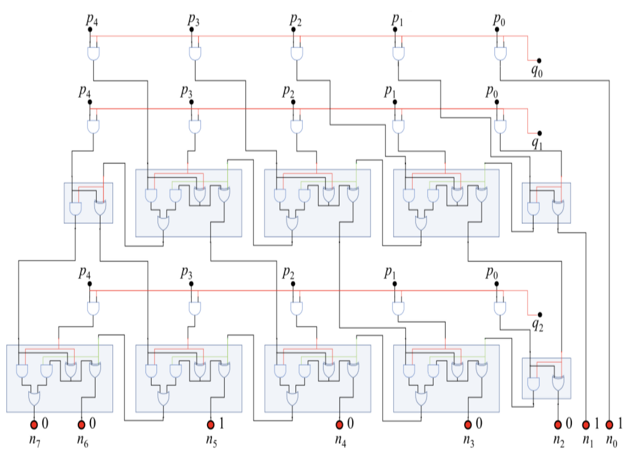
Multiple central processing units (CPUs) and parallel machines are becoming the norm in terms of computers these days. In such parallel machines, all CPUs are synchronized: each of them performs a task in an interval of time T. **At the end of the clock cycle**, and only at the end of the clock cycle, all CPUs share their results, and follow up with the subsequent task.

Intrinsic Parallelism

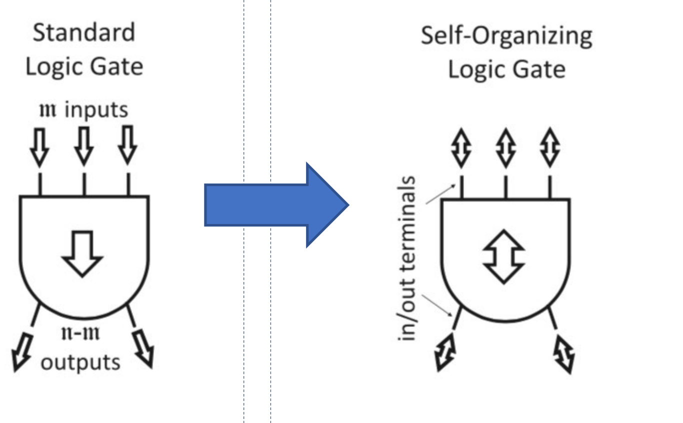


At any given time, any element of the machine "knows" what the other elements are doing. Indeed, the physical interaction among the different constituents of the machine provides collective dynamics to the whole system.

2 DIGITAL MEMCOMPUTING MACHINES (2/2)



A traditional Boolean circuit using logic Gate for prime factorization
It multiplies two integers p and q to give pq = n = 35 = $(100011)_2$ (in the little-endian notation).



Moving from traditional gates to terminal-agnostic gates

Finite precision thanks to SOLGs

Memory and self-organization allow us to build a new type of logic so that we can read & write the outputs & inputs respectively with finite precision. Since finite precision simply translates into expressing a problem in binary format, this means that DMMs are ideal for combinatorial/optimization problems. A Boolean problem can be transformed into a physical problem, so that we can solve it also in reverse. This allows us to invert the so-called “one-way functions”, namely, those problems, such as factorization of prime numbers , that are easy to solve in one direction but not in reverse mode.

Solving Boolean problem with DMMs

- Construct the Boolean circuit that represents the problem at hand
- Replace the traditional (unidirectional) Boolean gates of this circuit with SOLGs.
- The electronic circuit built out of these SOLGs can be described by differential equations
- Feed the appropriate terminals with the required “input” (e.g., the number to be factored).
- Build the corresponding circuit in hardware or simulate its differential equations in software.
- Find the equilibrium (steady-state) points of the dynamical system, which encode the solution

MINI-GLOSSARY

Terminal-agnostic Boolean logic does not distinguish between the input and output. DMMs built out of these new types of gates can self-organize, collectively, to solve hard problems very efficiently. DMMs perform computation embedded in memory, employing all of their fundamental units, at once, like a brain.

Mem-Elements
Can be defined as Electrical circuit elements with memory. Mem-Elements have been demonstrated to be good candidates not only for storing data but also to enable the building of a new generation of computational memories, i.e., memory devices that can perform basic computing tasks directly within memory.

Active Elements such as transistors are necessary to enable the modification of the system “on the fly”. Memcomputing machines would use only available materials and devices for such active elements.

3 Demonstrated Performance

Software simulations of DMMSs have already shown a considerable advantage over traditional (algorithmic) approaches.

Machine Learning

Simulations of SOLCs

- Provide a very good approximation close to the optimum
- Acceleration of the pre-training is comparable to the reported hardware application of the quantum annealing method implemented by the D-Wave machine
- Far better performance than the quantum annealing approach in terms of quality of the training: >1% in accuracy, corresponding to a 20% reduction in error rate.

A combinatorial challenge the Subset-Sum problem

The subset-sum problem belongs to the NP-complete class. Simulations of DMMs offer solutions to this problem in polynomial time vs. the exponential requirements of standard approaches.

- Solved using a standard algorithm approach implemented in Matlab: **2000 years**
- Memcomputing: **in a few days**

Max-SAT Optimization problem

The simulations of SOLCs using a sequential MatLab code perform orders of magnitude better than the winners of the 2016 Max-SAT competition on a wide variety of optimization problems.

- Random 2 Max-SAT,
- Max-Cut,
- Forced Random Binary problem
- Max- Clique

In some cases, the memcomputing approach finds the solution to the problem when the winners of the 2016 Max-SAT competition could not.

Integer Linear Programming

We have also succeeded in emulating DMMs using a new style of logic gate of our design, Self-Organizing Algebraic Gates. So, powerful, we have already solved numerous benchmarks in minutes, where others had failed using 1000's of compute hours.

Quantum computing too little too late?

Quantum Computing takes advantage of some features of Quantum Mechanics, especially entanglement, which allows a quantum machine to have its elements "correlate" with each other at very long distances, as if the whole system were "rigid": a perturbation in (measurement of) one of its parts, would be immediately felt in other parts arbitrarily far away. Entanglement then realizes an ideal long-range order, one in which the correlations do not decay spatially.

ADVANTAGES

Can solve a non-deterministic polynomial (NP) problem, such as factorization, efficiently, albeit probabilistically. Envisioned for applications to Materials Science.

LIMITATIONS COMPARED WITH DMMs

- **Need hardware: cannot be efficiently simulated in software.**
- **Not proved to efficiently solve difficult problems, such as NP-complete problems.**
- These machines need to work at **extremely low (cryogenic) temperatures,**
- Substantial **increase in hardware complexity**
- Difficulty to **scale them up to large size**

A Paradigm Shift

Instead of trying to force a physical system (like our modern computers) to represent a (mathematical) Turing machine, we conceived a completely different type of machine that takes full advantage of appropriately designed physical systems, and yet allows for read/write output/input digitally with finite precision that is independent of the problem size or complexity!

4 CONCLUSION

MemComputing introduces a new paradigm where highly complex problems are **converted from a combinatorial problem into a physics problem**. Solving the physical problem avoids the exponential explosion associated with current best in class heuristic approaches.

When SOLGs replace traditional logic gates, a self-organizing logic circuit (SOLC) is created. The dynamic, collective self-organization of all the SOLGs in the circuit allows SOLCs to converge into equilibrium points from any state selected at random. The equilibria represent either the exact solution of a decision problem or approximations for optimization problems that come closer to the global optimum than current best solutions.

This allows MemComputing to provide performance enhancements that are dramatically faster than other approaches, especially Quantum Computing.

- **Cheaper, simpler, years ahead of quantum computers**
- **Ultra-fast solutions, in particular for previously unsolved problems**
- **Emulated in software, it runs on traditional computers**
- **Computation & Memory Combined in the same circuit**
- **A brand new/patented computer architecture**
- **Uses classical low power, low heat transistor technology**

MemComputing, Inc.'s disruptive coprocessor technology is accelerating the time to find feasible solutions to the most challenging operations research problems in all industries. Using physics principles, this novel software architecture is based on the logic and reasoning functions of the human brain.

MemComputing enables companies to analyze huge amounts of data and make informed decisions quickly, bringing efficiencies to areas of operations research such as Big Data analytics, scheduling of resources, routing of vehicles, network and cellular traffic, genetic assembly and sequencing, portfolio optimization, drug discovery and oil and gas exploration.

The company was formed by the inventors of MemComputing, PhD Physicists Massimiliano Di Ventra & Fabio Traversa and successful serial entrepreneur, John A. Beane.

MemComputing Inc.
4250 Executive Square,
Suite 200,
La Jolla, CA 92037

http://www.memcpu.com
info@memcomputing.com